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A STUDY OF THE APPLICATION OF LASER TECHNIQUES TO WEAPON SYSTEMS (U)

(8)

by

(10) Donald R. Peterson

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Directorate of Research and Development
U. S. Army Missile Command
Redstone Arsenal, Alabama

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(C) ABSTRACT

This report presents the results of a detailed study conducted by the Advanced Systems Laboratory on weapon system concepts incorporating Laser Techniques.

The study consists of two parts. The first considers Laser kill mechanisms, and the second investigates guidance and control approaches.

Conclusions drawn from the study are presented.

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A STUDY OF THE APPLICATION OF LASER TECHNIQUES TO WEAPON SYSTEMS (U)

I. (S) INTRODUCTION

This is a report of the work performed by Advanced Systems Laboratory, Army Missile Command on the LASER (light amplification by stimulated emission of radiation) weapon system. Combat Requirements Branch, Future Missile Systems Division, Army Missile Command requested this Laboratory to postulate a tactical Laser weapon system. This postulation was conducted in two fields; (1) kill mechanisms and (2) guidance and control.

A Laser kill mechanism system has been proposed for four different ranges; 0.025, 0.25, 2.5, and 25.0 nm. A laser module having an average power of 1,018 watts is also proposed. This unit with the proper 2-msec pulselength is capable of effecting a kill against personnel and armor targets at the previously mentioned ranges. The study shows that the size and weight of the laser module and coolant will be negligible in comparison to the power supply required to drive the unit. Different types of power sources are also examined. The magnetohydrodynamic power source shows the greatest promise for the high powers required for the long-range kill mechanism.

For guidance and control applications, most of the work consisted of a study of the state-of-the-art of laser technology. A guidance system is now being formulated and a report will be written at the outset of the system's analysis.

Conclusions and recommendations are made at the end of this report.

II. (S) DISCUSSION

A. (S) Kill Mechanisms

1. (S) History of Laser Development. Laser history began in 1952 with the prediction by J. Weber that MASER (microwave amplification by stimulated emission of radiation) operation was possible. In 1955, C. H. Townes built the first operating maser using the ammonia molecule

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as an active substance. In 1956, N. Bloemberger proposed a solid-state maser.

An extension of maser principles to allow operation in the light spectrum was suggested by C. H. Townes and A. L. Schawlow in 1958. They predicted that in the resulting laser, coherent and monochromatic light would be produced.

T. H. Maiman, in 1960 produced the first operational laser, a pulsed affair using a ruby rod. Ali Javen, W. R. Bennett and D. R. Herriot developed a continuous-wave gas laser one year later. They used a helium-neon gas mixture excited by a radio-frequency field, and obtained an output in the infrared region.

A solid mixture of trivalent uranium in calcium fluoride was made to lase by P. P. Sorokin and M. J. Stevenson in 1960. They followed this experiment with experiments using other solid-state materials.

P. P. Kisliuk, W. S. Boyle and P. Leavy reported the first amplification of light using a ruby laser oscillator to drive a ruby laser final amplifier. Gains on the order of two times were reported. P. A. Franklin, A. E. Hill, C. W. Peters, and others achieved generation of optical harmonics using a laser source directed into a crystalline quartz. By frequency doubling techniques, the ruby output wavelength was halved from 0.6943 to 0.3472 µ. Coherence of the doubled wavelength light made was not measured.

At the present time, a number of firms are doing work on new lasing substances. One of the most hopeful materials is the neodymium-doped glass rod. American Optical has already made a number of these laser rods, one of which has been used to energies of 840 joules at 1.3 per cent efficiency. These figures are high for the present state-of-the-art.

2. (S) Basic Laser Theory. The word laser is an acronym of the job it does - light amplification by stimulated emission of radiation. Its predecessor, the maser, provided amplification with unprecedentedly low internal noise levels. The reason for this exceptional performance is that maser amplification does not involve charged particles in the form of free electrons as electron tubes do. Hence, it is not subject to the internal noises generated from the randomness in velocity of charge and the discrete nature of the charge.

In both maser and laser, the electrons are bound to the positive core of the nucleus and are thereby neutralized. The fact that these bound electrons can exist in different energy levels forms the basis for the theory of maser amplification. These energy states can exist corresponding to various orientation within a paramagnetic substance, or simply as discrete energy levels. In general, there are many such states.

The distribution of the paramagnetic atoms (as in the ruby laser) usually conforms to the Boltzmann distribution curve, which states that the ratio of the number of atoms in the excited state E to the number of atoms in the ground state E_0 is given by

$$\frac{N(E_1)}{N(E_0)} = \frac{e^{-E_1/KT}}{e^{-E_0/KT}} = e(E_0 - E_1)/KT$$

Hence, there are usually fewer atoms in the higher level than in the ground state.

Paramagnetic solid-state maser operation involves three energy levels: the ground state, and two excited states, E_1 and E_2. To overcome the normal Boltzmann distribution, and thus effect conditions for maser operations, an external pump is required. This pump energizes atoms in the ground state E_0 to E_2. By thermal interaction, the atoms in E_2 decay to E_1. Should this decay from E_2 to E_1 be fast enough, more atoms will jam the E_1 state than leave it in a decay to the ground state E_0. Thus, an inversion of the Boltzmann distribution has occurred. For this to exist in Boltzmann's equation, the temperature must become negative since K is Boltzmann's constant and cannot be changed. This effect is then called a "negative temperature distribution".

$$\nu = \frac{E_1 - E_0}{h} \quad \text{(Bohr's Postulate)}$$

After there is a sufficient unbalance in the E_1 and E_0 population, the induction of an outside signal of frequency will cause some of the atoms in E_1 to decay into the ground state and to liberate the difference

$$E_1 - E_0 = h\nu$$

in energy which is exactly in phase with the driving energy. Thus an amplification has been attained. Higher gains can be obtained by properly silvering the ends of the rods, or using Kerr cells and piezoelectric crystals as a means of feedback, thus forming a regenerative amplifier. Oscillation can be forced if the feedback amount is high enough. At

resonance, the small amount of thermal noise will be amplified and fed back into the system until a steady state is reached. This state is determined by the rate at which atoms are pumped into E_2 (see Figure 1).

The pump frequency obviously must be

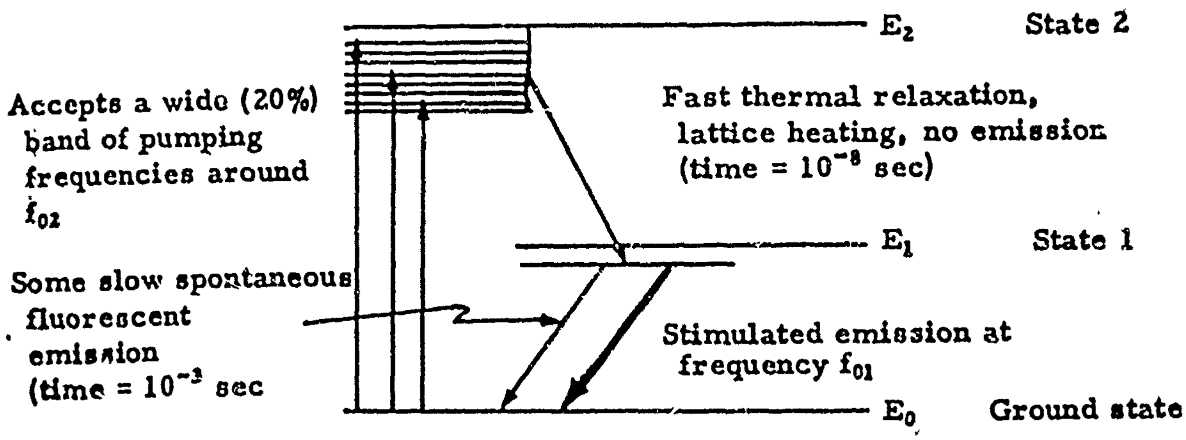
$$\nu = (E_2 - E_0)/h$$

to pump atoms from the ground state into E_2. Because some thermal decay is always present, it is necessary that $E_2 > E_1$, and by the same reasoning, the frequency of the pump must be greater than the frequency of the output.

Within a paramagnetic solid-state laser device, certain deviations from maser theory are evident. A ruby laser, for example, has an aluminum oxide crystal with a varying percentage of trivalent chromium ions interdispersed through the crystal structure. This doped crystal possesses very intense internal magnetic fields, permitting the trivalent chromium to exist in different magnetic orientations or energy levels. The transfer of energy from one level to another is similar to that which takes place in a maser except for two important differences. First, the frequencies involved are approximately 10^5 times higher than those involved in maser operation. Second, and most important, is the fact that the energy state E_2 is not a discrete line as in maser operation, but consists of a multitude of closely spaced levels. Thus, the effective absorption frequency range for the pump $\Delta\nu\rho = \Delta E_2/h$ is much greater than the absorption line of the maser. Hence, the ruby absorbs within a much broader band than the maser. A laser rod will absorb within the region of ± 20 per cent of the center frequency. This characteristic of laser absorption is very important, since no high power line sources (coherent sources) are available.

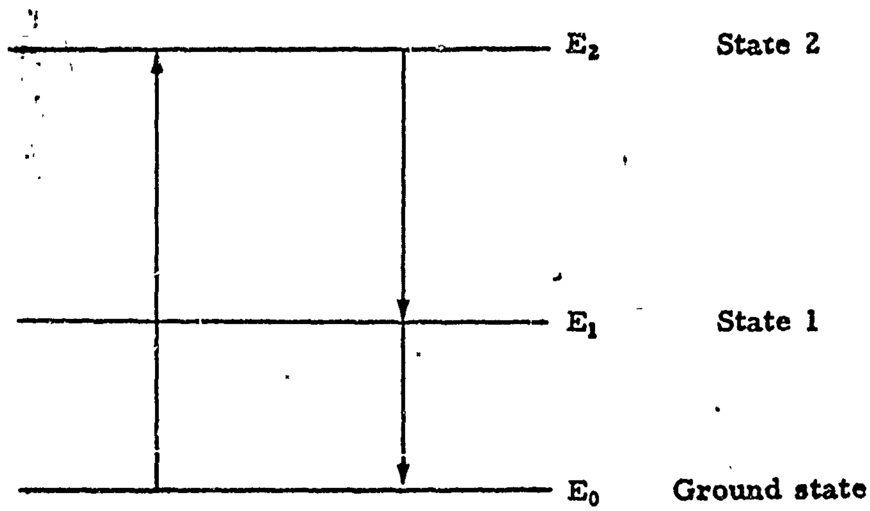
Spontaneous emission plays an important part in laser technology. In the maser, as the pumping power is increased to the threshold of maser action, the E_2 population builds up and decays by nonradiative thermal transitions. If maser pumping power is increased beyond the threshold of maser action, induced radiative transitions from E_2 to E_1 occur.

In the laser, however, when the pumping energy is below the threshold of laser action, most of the E_2 population decays to E_1 by a spontaneous emission of radiation (fluorescence). If the pump power is increased beyond threshold, induced radiative transitions occur similarly to those in maser operation.



$$f_{02} = \frac{E_2 - E_0}{h} \qquad f_{01} = \frac{E_1 - E_0}{h}$$

Pertinent energy levels for laser action in ruby



Typical paramagnetic maser energy level diagram

Figure 1. (U) LASER AND MASER ENERGY LEVELS.

The most important difference is that induced radiation is exactly in phase with the stimulating radiation, whereas spontaneous emission is random and not necessarily connected with a stimulating signal. The randomness of spontaneous emission constitutes the noise level in laser operation, whereas the induced emission is actually amplification. The probability of generating some spontaneous emission rises as the wavelength decreases; hence, the noise level in the maser is much lower than that in the laser.

The mode selection, or feedback, in a laser is obtained basically by using a set of Fabry-Perot plates operating in the ordinary form. Often these plates will be actually ground into the ends of the laser rod and appear as perfectly parallel mirrors.

If a laser has a uniformly-excited homogeneous rod with carefully aligned plates, the normal mode will approximate a plane wave. By use of Rayleigh's criteria for resolution it can be shown that for an aperture D, the angular width of the emitted beam is given by the expression

$$\alpha = \frac{1.220}{D} \lambda .$$

it is evident that coherent light (light at a single wavelength) would have the lowest angle of spread for a given diameter aperture.

Because of the extremely narrow bandwidth of a laser beam, the intensity of flux per unit cross-sectional area is many times greater than the intensity that could be obtained from an incoherent source.

3. (S) Military Applications of the Laser. Because intensities about one million times that of the sun are attainable from a laser with only a moderate input requirement, a military interest was developed, first as a type of kill mechanism and second as a method of guidance and control. Although the whole state-of-the-art is very young, available results show great promise in these two areas.

A practical, workable mobile device to meet close support requirements is greatly in demand. A laser beam would be difficult to track due to its extremely high velocity as opposed to the slower easier-to-track missile. Because coherent optical radiation is much more directive than other forms of electromagnetic radiation, the laser for kill applications currently shows the most promise for a "death ray" device.

Four ranges of an integrated field army laser system are postulated; the illustrative ranges assumed are 0.025, 0.25, 2.5, and 25 nm with each successive range being increased by one order of magnitude to encompass several field army applications. The first three will be considered primarily in a close-support role, and the fourth in a surface-to-air role. The purpose of the weapon is determined largely by its application at the time it is used and, therefore, considerable overlap is anticipated. The Laser weapon system is considered effective if it is able to immobilize the target. In most applications it will not be necessary to completely annihilate, disintegrate or vaporize the target. This assumption was made irrespective of whether the target was organic or mineral, or both. In fact, partial immobilization is actually more effective on manpower drain than a total destruction of the material involved. Wounded personnel require care, and disabled machinery needs repairs.

Vulnerable portions of a vehicle are tires, fuel tanks, track runner mechanisms, operating personnel, antennas, periscopes, ammunition magazines, electronic components and other vital areas.

Should the target be personnel, skin burns, brain, legs, eyes, and other vulnerable areas would be prospective targets. In this latter case, stunning, loss of motor control, or inability to reason properly for a relatively short period of time would constitute a "kill". The ignition of the enemy's uniforms would become enough diversion to consider the personnel involved as "killed". It is on this last criterion that the threat for personnel was developed.

4. <u>(S) Determination of Target Destruction Energies.</u> Figure 2 shows that 2×10^3 joules/cm^2 are required to melt a 0.1 cm steel plate. aluminum This value will be considered as a "kill" for the remainder of this report.

Table I shows the effects of burns on the human body. Incident energy versus thermal pulse rise time and duration to impart degrees of skin burns is shown in Figure 3. A soldier is combat effective if he is able to fulfill his assigned duties. Should he go into shock, or otherwise become disabled, he would be combat ineffective. A soldier who is combat ineffective, although unable to fulfill his duties, may not be casualty, since casualties are defined as those requiring medical attention. It has been shown that if 10 to 15 per cent of the body is covered with second or third degree burns, a state of shock results.

Table I

(C) RISE TIME AND PULSE FUNCTION, TYPES OF CLOTH AND INCIDENT ENERGY FOR DESTRUCTION

(1)

Rise Time: (sec)	0.042	0.32	3.3	
Pulse Duration: (sec)	0.42	3.2	33.0	
Material	Joules/cm^2	Joules/cm^2	Joules/cm^2	Damage
Cotton Twill, fatigue green, 8 oz/yd^2	33	59	105	Destroyed
Wool serge, winter service, OD, 9 oz/yd^2	88	159	276	Destroyed
Wool flannel, OD, 11 oz/yd^2	84	167	293	Destroyed
Cotton denim, blue, 9 oz/yd^2	29	54	96	Destroyed
Canvas, white, 12 oz/yd^2, untreated	50	88	155	Destroyed
Canvas, OD, 12 oz/yd^2, flame-proofed	21	38	71	Destroyed

(2) The table shown below defines the effects of burns in relation to the term "combat effective".

Body area	First degree burns	Second degree burns
Both eyes	Combat effective	Combat ineffective
Both hands	Combat effective	Combat ineffective
15% burns excluding hands and eyes	Combat effective	A few ineffective (10 to 15%)
25% burns excluding hands and eyes	Combat effective	Up to 50% ineffective

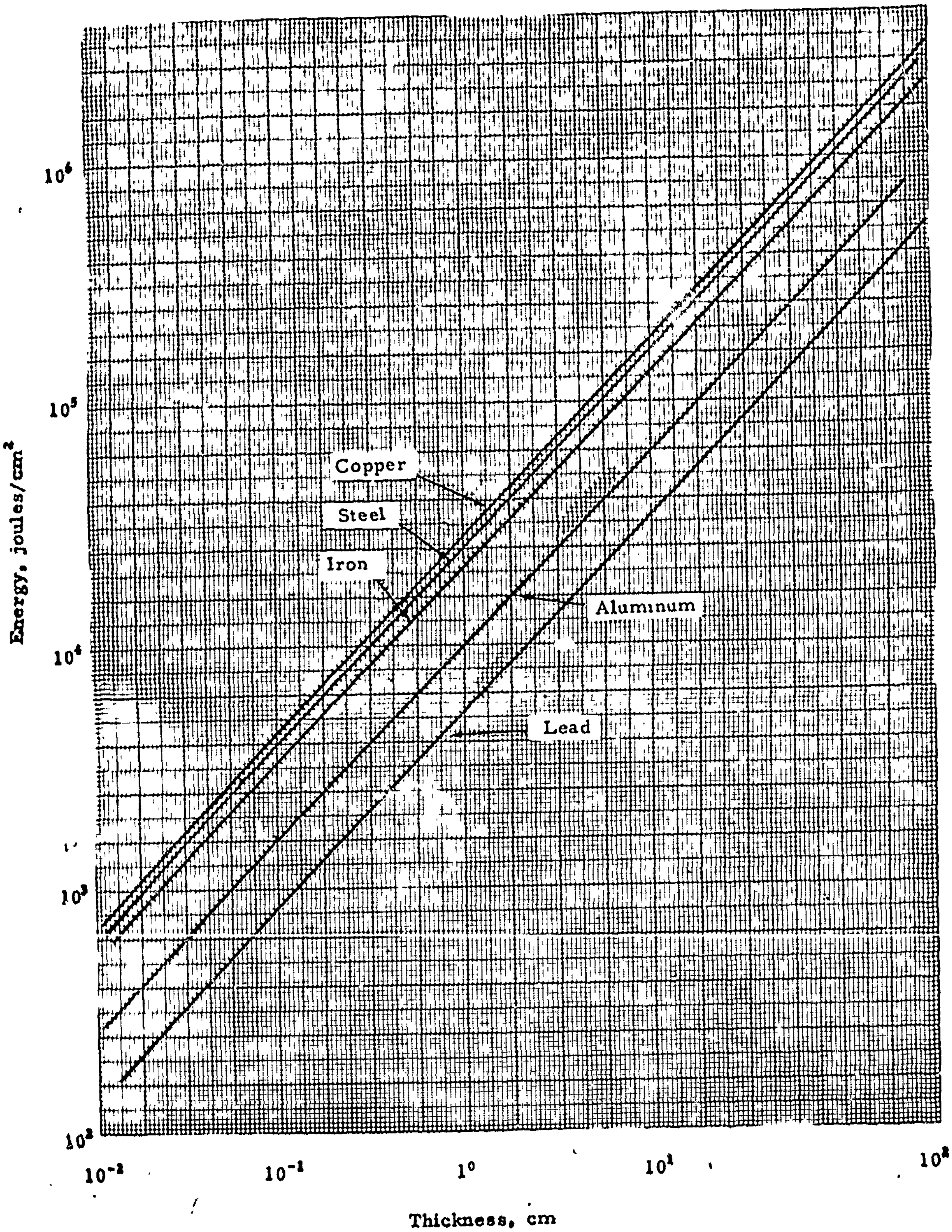


Figure 2. (U) INCIDENT ENERGY NECESSARY FOR VAPORIZATION.

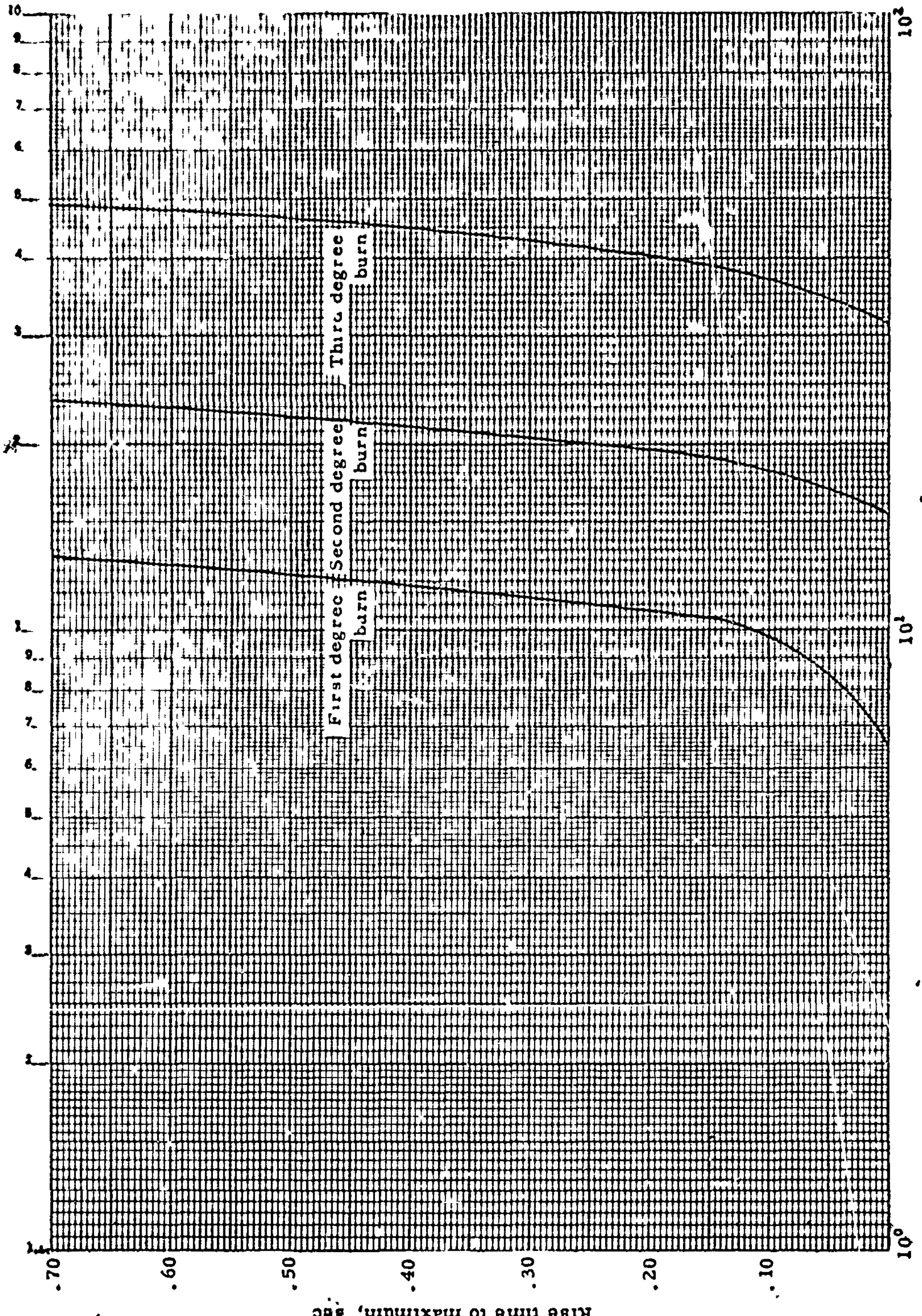


Figure 3. (C) INCIDENT ENERGY VERSUS THERMAL PULSE RISE TIME AND DURATION TO IMPART DEGREES OF SKIN BURNS.

Table I shows that a heavy winter uniform of wool requires about 50 joules/cm^2 of incident energy for ignition. The burning uniform is considered as having a diversionary effect on the soldier involved to render him combat ineffective. This value for an antipersonnel "kill" will be used throughout this report.

The pulselength for these effects will be about 1 msec and the power levels required to give the preceding effects will be as follows.

For antipersonnel,

$$\frac{50 \text{ joules/cm}^2}{10^{-3} \text{ sec}} = 50,000 \frac{\text{watts}}{\text{cm}^2} \text{ of incident}$$

energy to destroy the winter wool uniform.

For armor-piercing,

$$\frac{2 \times 10^3 \text{ joules/cm}^2}{10^{-3} \text{ sec}} = 2 \times 10^6 \text{ watts/cm}^2 \text{ of}$$

incident energy will be required to melt a hole in 0.1 cm of steel.

It must be remembered that the incident energies required for a "kill" will vary widely due to types of uniforms, different regional temperatures, types of steel encountered, and other similar factors. Although a great deal of testing and experimentation remain to be done in this field of laser technology to confirm true trustworthy values, it is felt that the orders of magnitude assumed are acceptable and will give a realistic set of input power parameters sufficient to determine the extent of feasibility of a laser weapon system.

5. <u>(S) Laser Module Configuration</u>. To obtain the high powers required for a "kill", special methods must be used. The proposed system will consist of four elements; a laser oscillator, and three power amplifiers.

The function of the laser oscillator is to supply a <u>2-msec</u>, coherent, low-power pulse to drive the final amplifiers. The reason for the 2-msec pulse will be discussed later. The oscillator output bandwidth must, however, be wide enough to cover the fluorescent line width of the material used in the final amplifier. The laser oscillator consists of four parts: (1) an optical pumping device, (2) a switching mechanism, (3) a beam converging system, and (4) a beam defining system.

The pump consists of the laser rod and the exciting flash-lamp (or other mode of excitation, such as gallium arsenide diodes) placed at the foci of an elliptical reflector. The bandwidth of the laser is directly dependent on the Q of the system which, in turn, is controlled by the pumping intensity and the albedo of the laser rod coating.

The laser rod consists of a neodymium-doped glass rod. Neodymium glass lases at 1.06 μ, which is in the near infrared, thus giving two advantages. The emitted beam is not visible to the naked eye, and the atmospheric attenuation at 1.06 μ is relatively low. Also, neodymium glass is relatively cheap to make compared to materials like chromium-doped ruby.

Pumping requirements must be considered. In neodymium-doped glass, a four-energy level laser material, only a relatively small fraction of the ground state ions needs to be pumped into an excited state to achieve useful gain. In contrast, the three-energy level ruby rod requires that more than 50 per cent of the ground state ions be pumped into the excited state before usefulness can be obtained. The active ion concentration in the neodymium-doped glass will exceed that achievable by the chromium ruby. The focusing effect of the rod enhances the pumping intensity throughout the extremities of the rod.

Within the laser oscillator there must be a method of feedback as described in the theory, and a Q switching device to control the pulse length. Changing the potential difference across a Kerr cell will produce this effect, but it has the disadvantage of requiring polarization for operation. Because of this, only one-half of the incident intensity to the polarizer is actually emitted. There are other methods of controlling the pulse. Figure 4 shows one of these methods, which uses two piezoelectric crystals mounted so that upon the impression of a voltage, one crystal expands, and the other contracts. The required conditions can be met by using 45-degree X-cut Rochelle crystals. The mirror fastened between the two will swing from parallel to a maximum displacement of about 5×10^{-4} radians, which would be enough to effectively switch the pulse on and off.

The second method, also shown in Figure 4, uses a piezoelectric crystal, but uses the torsional effects that can be obtained from certain cuts of these crystals.

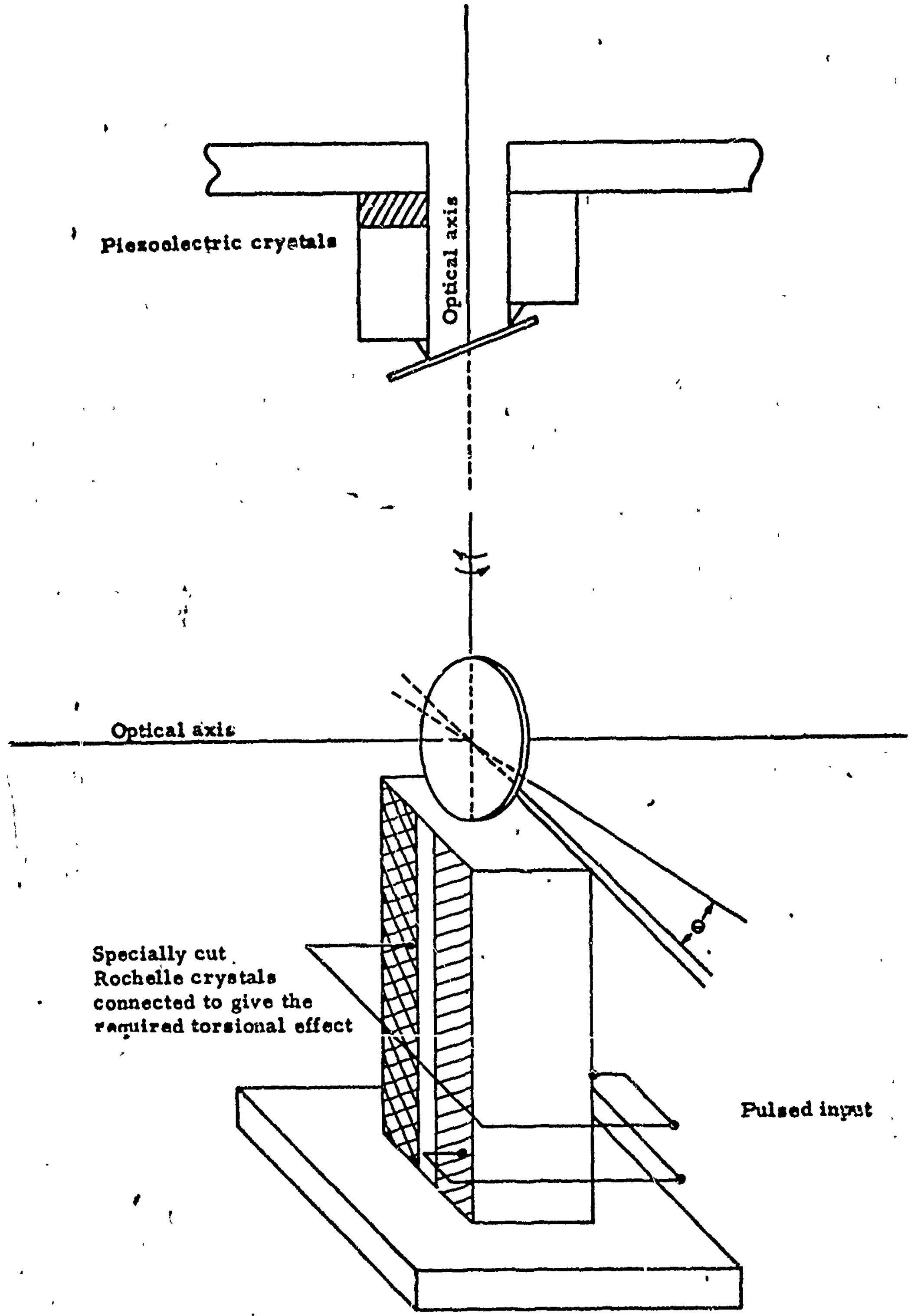


Figure 4. (S) LASER PULSING METHODS.

Cascading lasers by using the output of one to drive the next should produce a further gain. Cascading will have certain limitations similar to those encountered in a vacuum tube amplifier. Side effects such as noise, shot effects, and thermal agitation cause the gain of each stage to be progressively reduced. The axial coupling of each stage is extremely efficient due to the coherence of the output beam from the previous stage. Hence, the axial coupling efficiency, taken to be 95 per cent is within reason.

The coherent axial signal will be in phase with the transverse source and will be reinforced by it, thereby increasing the input over the output efficiency. The gains of the three stages of amplification decrease due to the noise, shot effects, and thermal agitation previously mentioned, and are assumed to be 1.25, 1.15, and 1.10, respectively.

The first two stages of laser amplification simply raise the output of the laser oscillator to a level sufficient to cause saturation of the final amplifier. The collimated beam from the oscillator is fed axially into the first stage of amplification, or the preamplifier, and is intensified, and the output beam enters the driver. The proper lenses and stops must be used between states to gain the full advantage of the collimated, coherent beam for a signal source. The driver further amplifies the beam and the resulting output beam is fed into the final or power amplifier. This final amplifier, because of the powers which have to be handled, will probably take the form of a number of laser rods paralleled and simultaneously excited by the driver. System configuration will be discussed further later.

The laser oscillator is pumped by a 1,000-watt unit, either flash tubes or gallium-arsenic photodiodes. Using the anticipated benefits normally gained by research and design efforts, a coupling efficiency between the pumping source and the laser rod is assumed to be 50 per cent with a 10 per cent efficiency of the lasing medium also assumed. These two extended considerations give only 5 per cent overall efficiency. However, it is believed that by taking advantage of triggering decay phenomena, extending pumping techniques, and applying the pulsed transmission mode approach, this efficiency can be extended to 20 per cent. Since those who propose these techniques predict an increase in power up to a factor of 100 over the original 5 per cent efficiency, the assumed 20 per cent value is equitable.

The preamplifier is pumped by a 1,000-watt pumping source. The axial input from the oscillator is 200 watts, and the gain of the preamplifier stage is 1.25. Hence the output of the preamplifier is

(1,000)(0.2) + (200)(0.95) 1.25 = 487.5 watts.

Similarly, for the driver stage, the rod is again pumped by a 1,000-watt pumping source. The axial input to this unit is 487.5 watts and the gain is 1.15. For the driver then,

(1,000)(0.2) + (487.5)(0.95) 1.15 = 763 watts output is obtained.

This 763 watts is fed axially into the final stage, which is transversely pumped by 1,000 watts. A gain of 1.10 is obtained, giving

(1,000)(0.2)+ (763)(0.95) 1.10 = 1,018 watts output from the laser system.

The sum of the inputs to the four sections of the system is 4 kw. The output is 1,018 watts, or about 1 kw. The overall system efficiency is then 25 per cent compared to the 20 per cent stage efficiency postulated. It must be remembered that 1,018 watts is an average power calculation. By pulsing methods, as will be shown, very high instantaneous power levels can be realized without exceeding the 1 kw average value allowed.

Such a goal has not yet been attained but some industrial researchers predict that as the state-of-the-art progresses, efficiencies of 50 per cent will be reached.

A threat has been developed and the requirements of 50 joules/cm^2 in the antipersonnel case and 2,000 joules/cm^2 in the antiarmor case have been resolved into the power concentration of 50 kw and 2 mw respectively, for a 1-msec pulse length. A laser module of 25 per cent efficiency has been proposed. The effects of beamwidth and atmospheric attenuation remain to be considered.

6. <u>(S) External Optics</u>. Very small beam widths will be required to concentrate the energy of the laser device into a small area a large distance away from the system.

Since the angular spread of a laser device without external optics is about 10^{-2} radians (a value currently obtained for ruby and applicable to the neodymium-doped glass), some method of narrowing the beam

must be employed. One means of obtaining the required increased directivity in the laser output utilizes a reversing telescope as shown in Figure 5. The angular spread θ_2 may be calculated as follows.

If the output of the laser has a spread of θ_2, then the diameter of the spot produced by this radiation at the focal point of a lens of focal length f_1 will be given by

$$d = \theta_1 f_1 \qquad \text{(for small } \theta_1\text{)}.$$

By using this spot as a source for the second lens of focal length f_2, the angular spread will be

$$\theta_2 f_2 = d$$

$$\theta_2 f_2 = \theta_1 f_1$$

$$\theta_2 = \theta_1 \frac{f_1}{f_2}.$$

It is easy to see that the directivity of the output of the combination can be made much greater by decreasing the ratio of $\frac{f_1}{f_2}$. This method can also serve as a ranging device. By a simple interchange of lens systems, different target areas can be available.

The reduction in angular spread is accompanied by an increase in the apparent diameter of the source. If Lens 1 is moved closer to the laser, the diameter of the spot of illumination on the lens will be approximately equal to d, the diameter of the output aperture of the system. The diameter of the corresponding spot appearing on Lens 2 will be proportional to the focal lengths of the lenses.

$$d_2 = \frac{f_2}{f_1} d_1.$$

Assuming a target illumination of one meter, it becomes necessary that the output aperture of the radiation weapon be smaller than one meter.

Then

$$\frac{f_2}{f_1} d_1 = d_2 < 1 \text{ meter}.$$

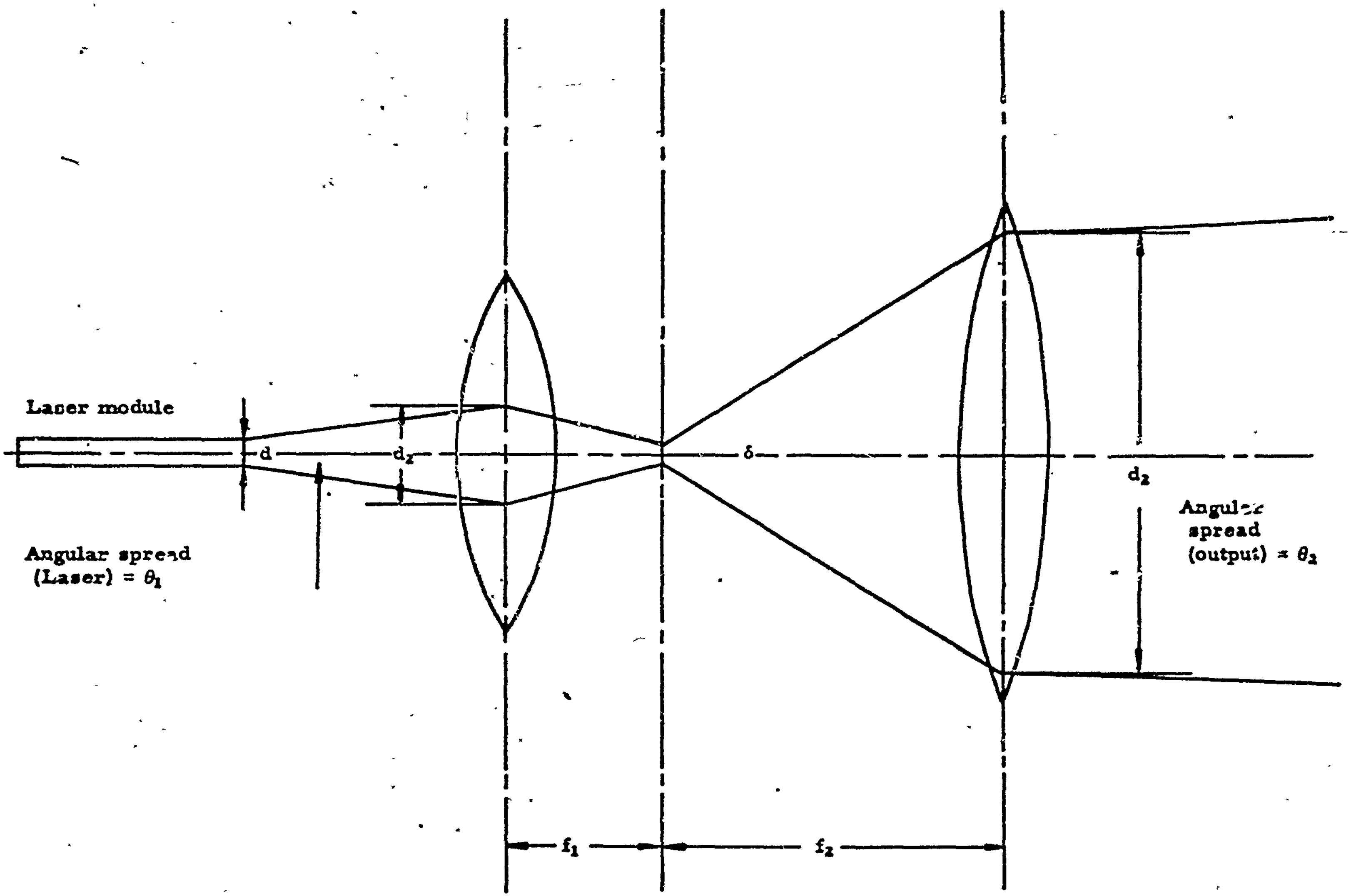


Figure 5. (U) PROPOSED LASER TELESCOPE.

If the angular spread θ_1 is 10^{-2} radians, as previously stated, and the desired spread is 2.5×10^{-5} radians, then

$$\theta_2 = \theta_1 \frac{f_1}{f_2}$$

$$2.5 \times 10^{-5} = 10^{-2} \frac{f_1}{f_2}$$

$$\frac{f_1}{f_2} = 2.5 \times 10^{-3}$$

and

$$\frac{f_2}{f_1} d_1 = d_2 < 1 \text{ meter}$$

$$\frac{f_2}{f_1} = \frac{d_2}{d_1}; \frac{f_1}{f_2} = \frac{d_1}{d_2}$$

then

$$\frac{d_1}{d_2} = 2.5 \times 10^{-3}$$

$$d_1 < 2.5 \times 10^{-3} d_2$$

and

$$d_1 < 2.5 \times 10^{-3} \text{ meter}$$

$$d_1 < 2.5 \text{ mm.}$$

If the lasing substance is more homogeneous, the angular spread θ_1 will be decreased, and a larger diameter laser rod can be used with this telescope to provide a beam of the required directivity and diameter.

The incident energy required to effect a kill is independent of range. However, the output of the Laser weapon system is affected by the losses encountered in any external optics used, the reflectivity of the target, and atmospheric attenuation.

7. (S) Atmospheric Considerations. The appendix to this report contains calculations of atmospheric attenuation within the infrared regions due to scatter and absorption. For low intensity beams this method of treating atmospheric effects is acceptable. However, a number of groups have theorized that at the high energies encountered in a laser beam, part of the pulse would literally burn a hole through the atmosphere, allowing the last part of the pulse to travel the clear path

with no attenuation. Because of the high-energy considerations, this theory appears plausible and will be incorporated herein.

Assuming that the power required to penetrate the atmosphere at normal densities near the earth is of the same magnitude as the power level required to effect a kill, a 2-msec pulse would be required from the laser device. The first millisecond portion is required to burn a hole through the atmosphere to one target, thus allowing the second millisecond pulse to pass unattenuated. Essentially then, there is a 50 per cent atmospheric transmission, independent of range, according to the assumptions made.

Combining the path portion of the pulse and the kill portion does not mean that the power supply is required to deliver double the power for 1 msec, but rather that it must deliver the immobilizing power successively for 2 msec, thus causing energy storage to become a power consideration. This pulsing can be compared to the form of pulse repetition used in radar. If, for example, the system were in operation for 2 msec, off for the next 248 msec, with a 4-cps reference time, the total "on" time would be 8 msec/sec and "off" time would be 922 msec/sec. This would become a duty cycle of less than one per cent. Should a 40-cps reference frequency (derived along with a 4-cps reference as a subharmonic of the standard 400-cycle supply commonly found in military equipment) be used, the total "on" time is 80 msec, "off" time is 220 msec, giving a duty cycle of less than nine per cent. A pulse repetition rate of 10 cps has been demonstrated in industry as feasible and within the time-thermal characteristics of the laser medium and the associated components.

A theoretical proposition of 100-per cent transmission, a reflectivity of zero per cent, and no losses in the external optics of the system enable the calculation of the power intensities required to effect immobilization at the target in the 0.025, 0.25, 2.5, and 25 nm cases.

Two considerations must be made for each range: the antipersonnel case and the antiarmor case.

8. (S) Antipersonnel Energy Calculations. A cross-sectional area of target has been assumed as 1 cm^2 for a kill, unless the angular spread of the output beam becomes less than the minimum of 2.5×10^{-5} radians set to attain the 1 cm^2 area. If the beam spread must be smaller than 2.5×10^{-5} radians to effect the 1 cm^2 target area,

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the area is calculated at the given range, due to a spread of 2.5×10^{-5} radians. For the 50-yard (0.025-nm) range, an angular spread of 2.96×10^{-4} radians effects a cross-sectional area of 1 cm^2 on the target. For antipersonnel, the kill required is 50 joules/cm^2.

Hence,

$$\frac{50 \text{ joules/cm}^2}{1 \text{ cm}^2} = 50 \text{ joules output from the}$$

Laser. However, the assumption that the amount of energy incident on the target is the amount of energy needed to cut through the atmosphere gives 100 joules output for the Laser. To attain this

$$\frac{100 \text{ joules}}{0.25 \text{ efficiency}} = 400 \text{ joules in.}$$

$$\frac{400 \text{ joules}}{2 \times 10^{-3} \text{ sec}} = 200 \text{ kw input to the Laser}$$

needed.

By similar reasoning, for the 0.25-nm system, 2.46×10^{-5} radians allow an illuminated target area of 1 cm^2. The powers would therefore become the same for this system as for the 0.025-nm range.

In the 2.5-nm range unit, however, the minimum proposed divergence angle of 2.5×10^{-5} radians gives a spread greater than 1 cm^2.

The incident area for this minimum angle can be found as follows.

$$\theta \text{ (radians)} = \frac{\text{Diameter of spot}}{\text{Range}}$$

and

$$A = \frac{\pi D^2}{4};$$

thus

$$A = \frac{\pi \theta^2 R^2}{4}$$

$$A = \frac{(3.14)(2.5 \times 10^{-5})^2 (457,200 \text{ cm})^2}{4}$$

$$A = 100 \text{ cm}^2.$$

The incident energy for antipersonnel is 50 joules/cm^2; hence,

$$\frac{(50 \text{ joules})}{\text{cm}^2}(100 \text{ cm}^2) = 5,000 \text{ joules of}$$

radiation required at target.

Because of the atmospheric effects, 5,000 joules are needed to penetrate it. The total output of the Laser is 10,000 joules at 25 per cent efficiency; 40,000 joules input are needed.

Powerwise,

$$\frac{40,000 \text{ joules}}{2 \times 10^{-3} \text{ seconds}} = 2 \times 10^7 \text{ watts input.}$$

For the 25-nm antipersonnel weapon system, an angular spread of 2.5×10^{-5} radians would illuminate

$$A = \frac{\pi D^2}{4}$$

$$A = \frac{\pi \theta^2 R^2}{4}$$

$$A = (3.14)(2.5 \times 10^{-5} \text{ rad})^2 \left[(25 \text{ nm})(1.8 \times 10^5 \frac{\text{cm}}{\text{nm}}\right]^2$$

$$A = (3.14)(2.5 \times 10^{-5})^2(4.572 \times 10^6)^2$$

$$A = 10,000 \text{ cm}^2.$$

The area illuminated on the target at 25 nm,

$$\frac{50 \text{ joules}}{\text{cm}^2} \times 10,000 \text{ cm}^2 = 500,000 \text{ joules}$$

of total energy needed on the target. A 50-per cent attentuation allowance would give 10^6 joules necessary out of the Laser. At 25 per cent efficiency, then, 4×10^6 joules input would be necessary to effect a "kill" at 25 nm.

9. (S) Antiarmor Energy Calculations. To meet the armor threat proposed at 50 yards, 10^6 watts are required. The same value will meet the requirements at 0.25 nm (500 yd) with proper focusing effects.

For the 2.5-nm weapon,

$$\frac{2{,}000 \text{ joules}}{\text{cm}^2} \times 100 \text{ cm}^2 = 2 \times 10^5 \text{ joules total}$$

required on the target.

The output of the Laser must be 4×10^5 joules which is

$$\frac{4 \times 10^5 \text{ joules}}{2 \times 10^{-3} \text{ seconds}} = 2 \times 10^8 \text{ watts.}$$

The power required to meet the armor threat proposed at 25 nm would be

$$\text{Incident power} = (10^5 \text{ cm}^2)\frac{(2 \times 10^3 \text{ joules})}{\text{cm}^2}$$

$$= 2 \times 10^8 \text{ joules.}$$

With a 50 per cent atmospheric transmission, 4×10^8 joules would be necessary out of the Laser. At 25 per cent efficiency, 10^9 joules input would give the kill effect desired.

10. (S) Weight and Cooling Parameters. The power-handling ability of the laser medium must be considered before a system can be said to be feasible. Because very limited data are available for neodymium-doped glass, and since the values vary widely from doping to doping, the following example will use values for the trivalent chromium-doped ruby rod. The principles are the same, however, and from the state-of-the-art in neodymium glass, it appears that this type of lasing material will give more favorable power-handling values than the ruby.

The volume and weight of 50-yard range ruby laser unit, consisting of four laser rods (three stages) in a cascaded module are estimated as 2.0 cm^3 and 6.0 grams.

For the 500-yard unit, these values become 20 cm^3 and 60 grams. For the 2.5-nm unit they are 120 cm^3 and 360 grams, and for the 25-nm, the ruby volume is about 1,200 cm^3, or about 73 in.^3, and the weight is about 3,600 grams, or 8 pounds. As previously mentioned, other media show great theoretical promise and, if used, will obviously affect the preceding values. However, as will be shown, the weight and volume of the laser itself will be comparatively insignificant in comparison to the parameters of the power supply driving the laser units. Including the weights and volumes of the associated pumping

devices, optical equipment, and other accessories will increase the laser volumes and weights by a factor of five. Allowing for the proper focal lengths, the laser module volume will be increased by an additional factor of ten. Here, as in most cases where volume is considered, the shape it takes is very important. In the laser module postulated, the major dimension is length and it is anticipated that the ratio of the length to the cross section or length to diameter will be a factor of about ten to one. The total weights for the entire laser assemblies, less power supplies and coolant, will be 30 grams and 100 cm^3 for the 50-yard range unit, 1,800 grams and 6,000 cm^3 for the 2.5-nm unit, and 18,000 grams and 60,000 cm^3 for the 25-nm unit.

If water is used as the coolant, the weight of the amount required is estimated as 45 grams for 500-yard range unit, and 450, 2,700 and 27,000 grams for the other ranges, respectively. These values can be easily converted into gallons. For the 2.5-nm range, the volume of water is three-fourths gallon and for the 25-nm range, the required volume of water is seven gallons. The cooling system will be a fan-driven air-water heat exchange unit. The newly developed refrigerants not susceptible to low-temperature environments are also quite practical and would eliminate the need for using additives in the water to lower the freezing point. Although it may appear that the use of air directly for the 50 to 500-yard ranges, and the elimination of the forced air requirement for the 50-yard range would decrease the size and weight, overall weight and space would remain essentially the same because the physical cooling area would be increased due to the extra fins and corrugation needed.

Table II summarizes the characteristics of the laser modules, not including power supplies. It should be recalled that the values given in this table may vary by several orders of magnitude depending upon focusing effects, target material and atmospherics. This table is meant to summarize the proposed system under the conditions stated.

11. <u>(S) Power Supplies</u>. It is evident that neither the space nor weight requirement for the Laser system as a complete module, including the cooling weight less the power generating equipment, represents a serious obstacle. The weight and space requirement for the 50-yard Laser for example lends itself readily to a handcarried infantry weapon but the mobility is somewhat impaired when the necessary power source is added. In this case, as a handcarried weapon, fuel cells appear to be the logical approach. A well-designed hydrogen-air

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(S) TABLE II. LASER MODULES LESS POWER SUPPLIES

Area	0.025 nm	0.25 nm	2.5 nm	25 nm
Type pumping	Electric	Electric	Electric	Electric
Type medium	Dpn Nd or Ruby	Dpn Nd or Ruby	Dpn Nd or Ruby	Dpn Nd or Ruby
Cascaded stages	4 (3 amp)	4 (3 amp)	4 (3 amp)	4 (3 amp)
Beam focusing	Optical	Optical	Optical	Optical
Beam spread	2.4×10^{-4}r	2.4×10^{-5}r	2.5×10^{-5}r	2.5×10^{-5}r
Overall efficiency	25%	25%	25%	25%
Energy at target				
Antipersonnel	50 j/cm^3	50 j/cm^3	50 j/cm^3	50 j/cm^3
Input to Laser	200 kw	200 kw	2×10^7 watt	2×10^9 watt
Laser output	50 kw	50 kw	5×10^6 watt	5×10^8 watt
Antiarmor	2×10^3 j/cm^3	2×10^3 j/cm^3	2×10^3 j/cm^3	2×10^3 j/cm^3
Input to Laser	4×10^6 watt	4×10^6 watt	8×10^8 watt	8×10^{10} watt
Laser output	10^6 watt	10^6 watt	2×10^8 watt	2×10^{10} watt
Type cooling	Air	Air	Air-water	Air-water
Overall module weight (including cooling)	75 grams	750 grams	4,500 grams	45,000 grams
Overall module volume (including cooling)	75 cm^3	750 cm^3	4,500 cm^3	45,000 cm^3
Pulse repetition rate	4/sec	4/sec	4/sec	1/sec***

*** Explained in text to follow

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(hydrox principle) fuel cell has a power volume density of 2 kw/ft^3 and a volume weight density of 50 lb/ft^3. In operation, the cell will require approximately one pound of hydrogen to produce 10 kw hr of electricity. To satisfy the power requirements of the 50-yard range portable Laser, two fuel cell power packs will be required, representing a total power supply weight of approximately 100 pounds as compared with 75 grams for the laser module. The net cabling weight with connectors is estimated to be 10 pounds and the pulse-forming capacitor-type (energy storage) electronic network is estimated as 15 pounds, giving a total system weight of less than 130 pounds.

A major advancement over conventional capacitors is currently under development and promises to give the same general performance with higher voltage capabilities and at one-third the weight and volume. The purpose of such a device is two fold; energy storage and pulse shaping. Pulse shaping is similar to an electronic RC or LC time constant device, and in this case uses the impedance of the circuitry in conjunction with threshold triggering or pulsing.

The purpose of energy storage is to accumulate comparatively low average power over a period of time ("off" time) and to release this as a peak burst of power in a short "on" time. In such manner, a power source having a reasonable rating level can be utilized provided the power source can withstand an unavoidable heavy drain during the early portion of "charge" and is capable of satisfying the "on" time needs during the "off" time allocated. For these reasons, in the case of the handcarried weapon, two fuel cells are employed in lieu of four although the same reasoning is applicable to the longer range weapons. It should be noted that the peak energy requirement of the laser module has not decreased, but that by using an energy storage device, the prime power source capacity has been reduced. For the purpose of this study the reduction from peak to average for that portion was estimated as two to one. Considering the PRF, such reduction is very modest. Some designers have considered "dry" cells (primary batteries) as ample for laser ranging purposes.

The weight of the short-range laser handcarried weapon will be distributed among three men. Two of these men will each carry a fuel cell and the third man will carry a lighter load, affording greater agility in aiming the weapon. The volume of pulse forming and energy storage electronic network is assumed to be 2 ft^3. Cooling is envisioned as being of the feel type to facilitate handling, and possibly with the cable under

slight tension to allow for connection and readiness during reconnaissance movement. Fuel cells of the type suggested feature minimum noise level and minimum signature to the enemy, and can produce useful, palatable water as a by-product. Daytime sighting is accomplished by normal rifle techniques aided by optics when necessary or desirable. Nighttime sighting could be implemented by infrared illumination or "snooper scope" applications or by an adaptation of the sighting capabilities of the Laser weapon. The latter, however, will place a greater demand on the system both in the area of power and cooling. The effectiveness of the 50-yard weapon does not lie in range but in quietness and low detectability. Its range would exceed that of a flame thrower, and it would have obvious advantages.

12. (S) Mounting and Transportation. The power input requirements of the 500-yard Laser weapon exceed the handcarried category and must be vehicle mounted to retain mobility. A lightweight wheeled vehicle, such as the M422 jeep with a 45-kw electrical generator coupled to the engine as a power take-off and feeding the laser module, would make the system an effective longer range antipersonnel weapon. Although this vehicle-mounted Laser system would be no match in a standfast tank duel, under certain conditions, with proper screening or natural camouflage or when undetected, it could be used in a shoot and scoot antitank role if the tank-operating personnel are concentrated upon by way of the tank-mounted periscope or tank-sighting slots. In this manner its field army use would be somewhat analogous to the bazooka but with greater range. In lieu of a power take-off to a rotating type generator, the vehicle could be electrified as described later for the longer ranges, offering an advantage of making available alternating current at almost unlimited frequencies and/or direct current independent of engine speed. In any event, the horsepower capability of the standard jeep vehicle engine would not be sufficient to power both the vehicle at full speed and the Laser weapon simultaneously. Therefore, shoot and scoot is mentioned. For the jeep, shoot and scoot does not necessarily mean the vehicle must be brought to a stop before the weapon is brought into play, but it does mean that the power output available for locomotion is limited to approximately one-fourth or less of rated values. Although increased engine size would circumvent this problem, it would entail redesign of other portions of the standard jeep vehicle and the problem may reduce itself to a desirability to be reasonably at rest in rough terrain to facilitate weapon aiming and kill probability in the least amount of time.

Sighting methods for day and night operation are of the same type as described for the 50-yard handcarried weapon. Weight of the generator and associated accessories is estimated as 550 pounds and that of the pulse shaping energy-storage electronic networks as 75 pounds. Again the laser module weight is insignificant so that the overall weight of the system, less the vehicle, is about 625 pounds. Allowing 225 pounds combined weight for the driver and Laser operator, this totals 850 pounds or the rated cross-country road capability of the standard jeep. Volume of the power supply and the pulse-shaping network is taken as 15 ft^3 and offers no problem. Total overall weight of the system, including the vehicle and total overall volume, falls within the design limitations imposed by Berne Tunnel restrictions and air dropability (see Figures 6 and 7).

Operation of the 500-yard Laser jeep weapon in a more standfast solely antitank role other than described will require a considerably higher level of power and no longer utilize the jeep as a single carrier. The jeep in conjunction with a drawn trailer may be possible but the level of power required warrants a more practical approach in a single vehicle for the longer range weapons as described later. However, if a trailer approach is desired, a magnetohydrodynamic (MHD) power supply should be mounted on the trailer and the vehicle engine generator output previously described used to satisfy the electromagnetic requirements of the MHD.

Such a system is basically the same as later described for the 2.5- and 25-nm Laser weapons and differs only in that the system components are distributed on two carriers, one of which is self-propelled. The total weight, less the carriers, for using the 500-yard Laser weapon in a more direct antitank role is estimated as 1,850 pounds, 1,000 pounds of which is located on the trailer. This is the rated towed load allowance of the jeep. Again, volume presents no acute problems.

For the 2.5 and 25-nm Laser weapons the power requirements pose a much greater problem. The power, weight and cooling suggest that a tank chassis will be needed to assure a measure of mobility. For example, although a homopolar machine (acyclic) appears to be the most logical rotating equipment, this machine's flywheel inertia as stored energy is too heavy for a mobile unit. Also it requires too much time to bring the flywheel up to speed from rest and up to speed from about 60 per cent speed after each firing.

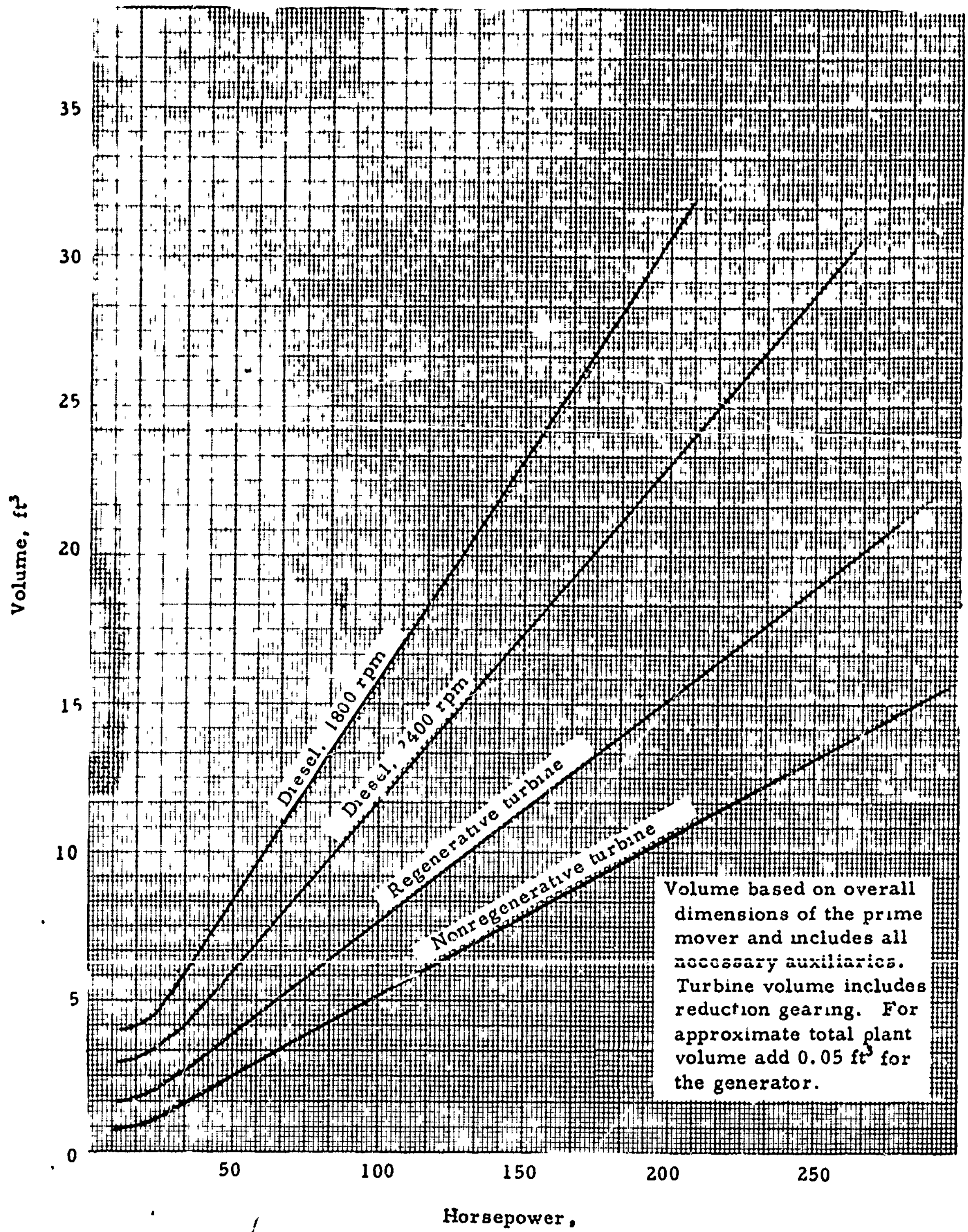


Figure 6. (U) TYPICAL COMPARISON CURVES OF VOLUME VERSUS HORSEPOWER FOR DIESEL AND TURBINE PRIME MOVERS.

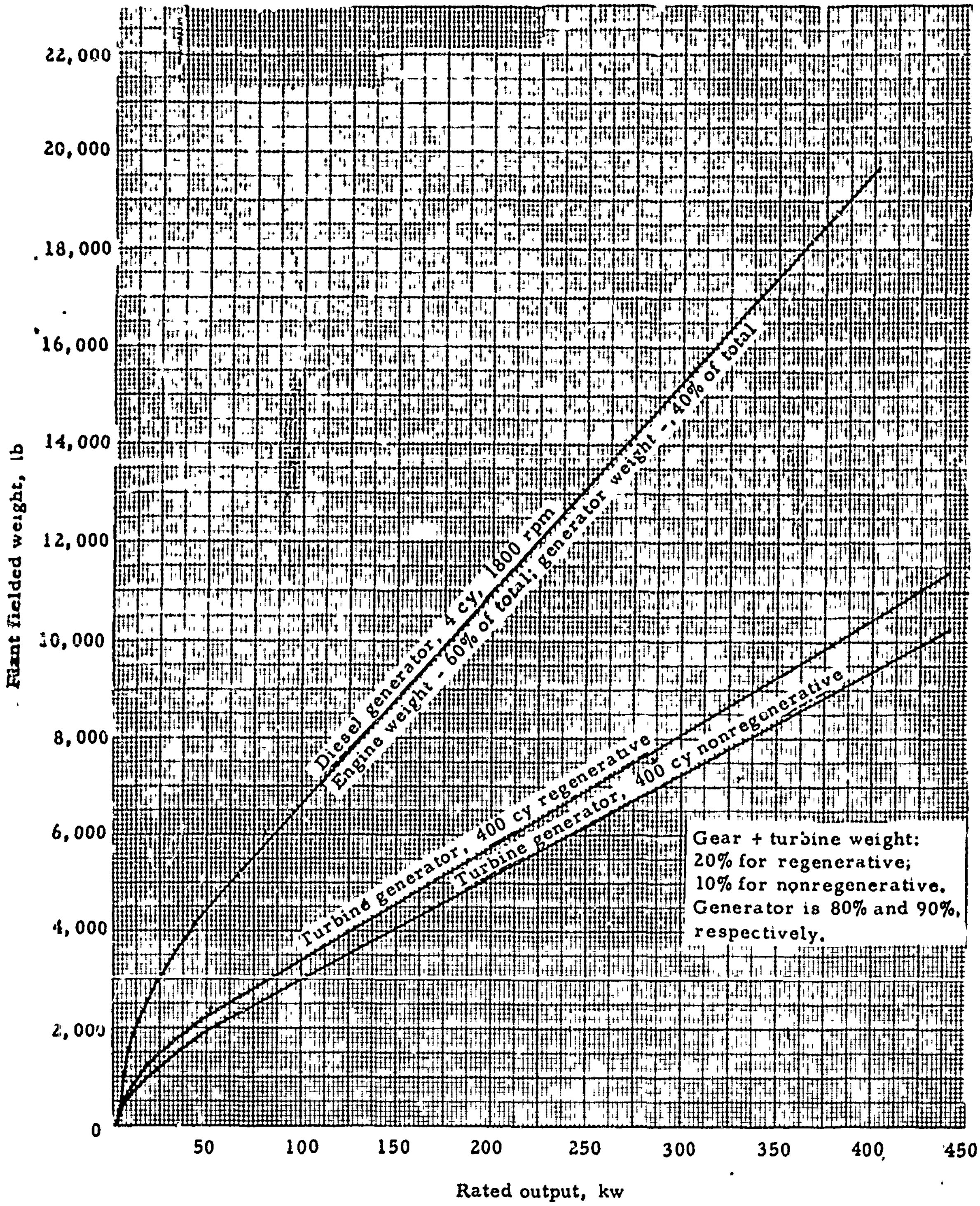


Figure 7. (U) TYPICAL COMPARISON CURVES OF FIELD WEIGHT VERSUS KILOWATT OUTPUT FOR DIESEL AND TURBINE GENERATOR PLANTS.

Data on turbines, both regenerative and nongenerative, as well as for diesel and ignition spark have been compiled in Figures 8 through 10 and show the relative characteristics of each type.

13. (S) Magnetohydrodynamic Generators. A power supply system best suited for heavy peak power needs appears to be the MHD generator, but it requires research and development and its state-of-the-art is at the same relative level as laser technology.

The MHD generator, sometimes referred to as the plasma generator, contains no moving parts and utilizes a magnetic rather than an electric field to accelerate the charged particles. The plasma is made conductive by partial ionization and is forced to cut the magnetic field. Unlike most other power sources, the efficiency of the MHD increases with size so that in the larger sizes the efficiency is expected to approach 75 per cent with a power weight and power volume density more favorable than conventional heavy-duty generating equipment. One limiting parameter to date for the MHD is its inability to generate large blocks of power for long periods of time. This is due mainly to the state-of-the-art, but is not a serious drawback for the Laser application postulated since these use bursts of peak power for short durations.

A 200-kw MHD unit capable of producing that level of power for one minute has been demonstrated and the industry feels that this can be scaled up to 500 kw. Even this level falls short of the maximum requirements of the antiarmor Laser system for the 25-nm range. However, by utilizing proper pulsing control, or surging, a level of about 16 mw for 500 msec, or 160 mw for 50 msec would be possible within the time-thermal boundaries. It may be practical and advantageous to control the overall Laser weapon PRF by controlling or triggering the MHD surges. By similar time-thermal reasoning, such an MHD generator could be expected to produce 15,000 mw of peak power for 2 msec, which exceeds the 25-nm antipersonnel laser energy storage device peak power requirements per pulse by approximately five times. It should be pointed out that this factor of five is theoretical and that a practical anticipation reduces this figure considerably due to inherent electrical and magnetic recover-delay-heat problems.

Industrial researchers expect an MHD tube 10 feet long and 1 foot in diameter to produce about 100 mw or 10 mw/ft^3. This power-volume density is reduced by one-half to compensate for electromagnetic components, pumps and associated auxiliaries, but does not include

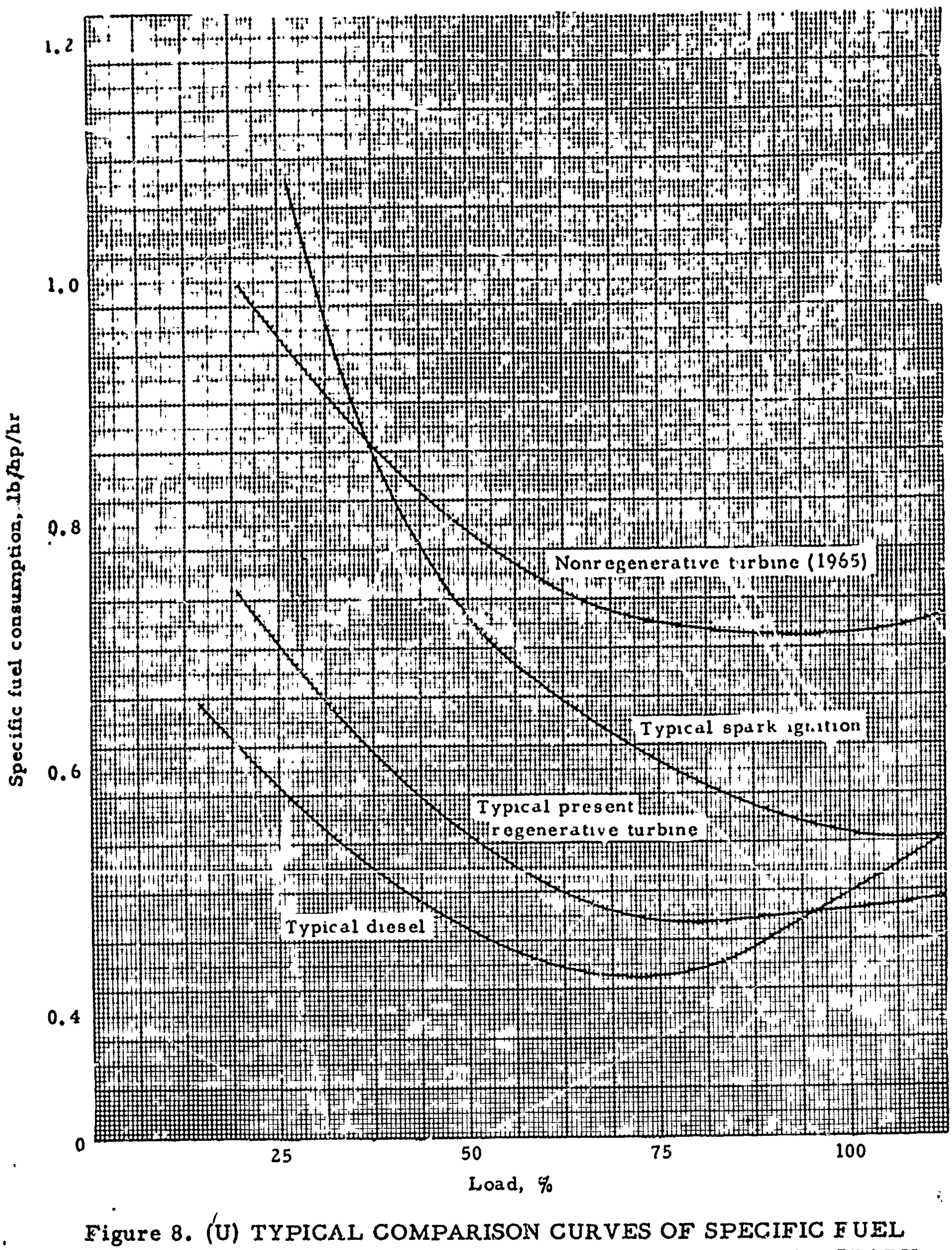


Figure 8. (U) TYPICAL COMPARISON CURVES OF SPECIFIC FUEL CONSUMPTION VERSUS PER CENT LOAD FOR SPARK IGNITION, DIESEL AND TURBINE PRIME MOVERS.

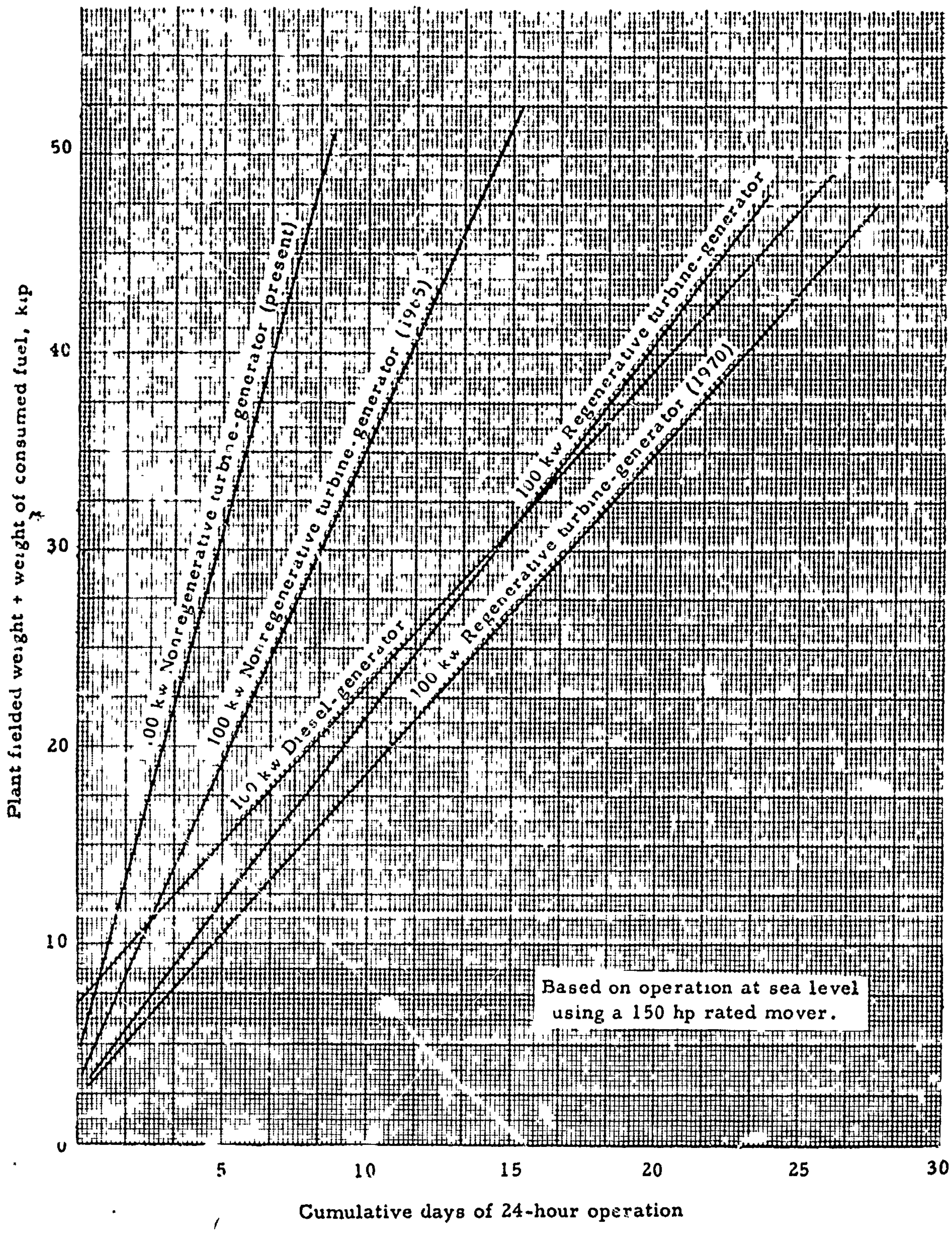


Figure 9. (U) TYPICAL COMPARISON CURVES OF PLANT AND FUEL WEIGHT VERSUS DAYS OF OPERATION FOR DIESEL AND TURBINE 100-KW GENERATOR PLANTS.

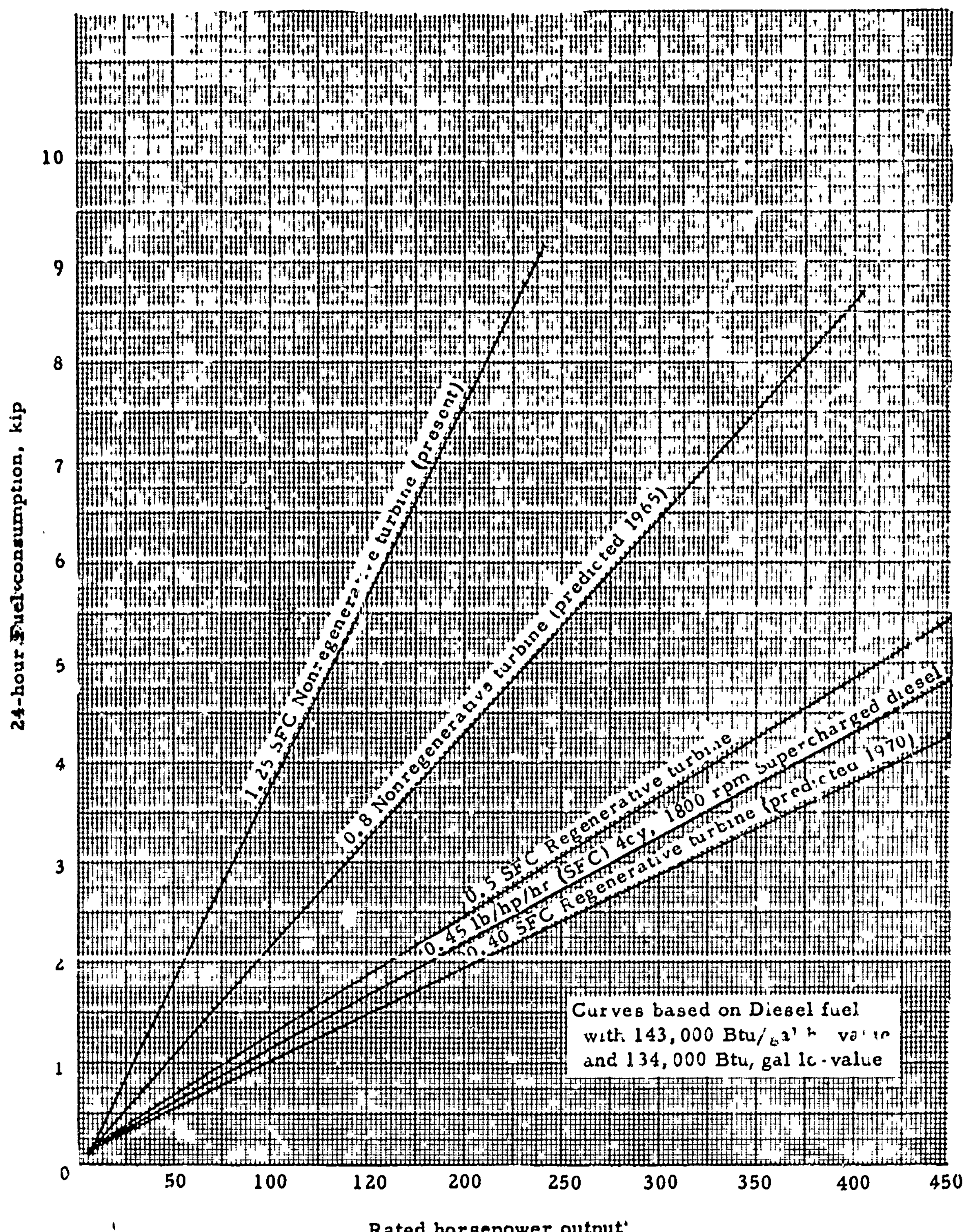


Figure 10. (U) TYPICAL COMPARISON CURVES OF HORSEPOWER VERSUS FUEL CONSUMPTION FOR DIESEL AND TURBINE PRIME MOVERS.

power input equipment to the MHD and cooling, so that the power volume density becomes 5 mw/ft^3. A further reduction is allowed for the air-water (or other) heat exchangers by the same factor so that the overall MHD power-volume density is set at 2.5 mw/ft^3.

For the 2.5-nm Laser therefore, the total MHD volume becomes approximately 6 ft^3, and for the 25-nm weapon it becomes approximately 60 ft^3. Physically, in the case of the latter, it is estimated that the MHD power plant will be about 3 by 2 feet in cross section and 10 feet long, with length being the most critical parameter. Volume-weight density is estimated to be 150 lb/ft^3 average using 500 lb/ft^3 for the heavy electromagnetic portion of the MHD.

For the 2.5-nm laser magnetohydrodynamic plant this amounts to 900 pounds, and with the laser (including the electronic pulsing and storage network) and coolant it totals approximately one-half ton. An M113 tracked vehicle, which will be discussed further, is considered suitable for the 2.5-nm Laser weapon in the role of an antitank and low-medium altitude antiaircraft weapon. The added one-half ton weight estimated for the laser and MHD modules is within or at the loading, transportability, and air dropability restrictions of the M113. A wheeled vehicle, such as the GOER, is also possible although additional modifications for light armor protection should be included.

Total weight of the 25-nm Laser and power plant module (including pulsing and storage network) is estimated at five tons.

14. <u>(S) Additional Prime Mover Considerations</u>. An additional role for the system could be as an antimissile weapon. It would be particularly effective against missiles during the powered portion of their trajectory since during this phase the missile would be the most susceptible to deviation and self-destruction. A slight deviation during the boost portion will result in a major deviation from intended impact. While the booster or powered portion of the missile is still attached, an overall greater target area is presented and more sensitive vital components are made available as targets. Stress damage sufficient to result in self-destruction will be afforded greater opportunity timewise when inflicted during the initial phase. Results of immediate damage, e.g., warhead detonation, could conceivably be confined to enemy held territory provided a firing position could be gained within range of the boost area or in the near vicinity of the launching site.

As laser and magnetohydrodynamic technology advances, effective weapon range will expand accordingly. Mobility of the 25-nm Laser is envisioned as being provided by the M60 medium tank chassis. Volume requirements for the complete weapon system (less vehicle) is estimated at 600 ft^3 with an average cross section about 6 by 5 feet and an average length of 20 feet. The volume of the 25-nm Laser weapon is more critical than its weight but the possibility of protruding part of the system, particularly the Laser optical system, external to the turret similar to a gun barrel will lessen this problem considerably. The gun barrel of the M60 tank presently extends approximately 15 feet beyond the turret and the turret ring diameter is approximately 7 feet.

Thus far, input power to the magnetohydrodynamic generator has not been discussed other than to mention it would be supplied by the on-board vehicle prime mover. Although the concept of on-board electrical power generation using the vehicle engine (shoot and scoot as before) is in itself reasonably simple, some complications arise when the concept is married to the MHD and laser modules. Studies and prototypes of electrified vehicles are currently in progress by industry under contract to army agencies. Modifications to the M113 and GOER are examples of electrical drives or electrical power assists under study. Some army vehicles have been outfitted with electrical drives in whole or in part and are undergoing tests. In these, basically a standard vehicle prime mover, the regular engine, which is usually a diesel, mechanically powers an electrical generator which in turn electrically powers individual wheel motors. In this system the motors are frequency sensitive and the generator frequency is controlled independent of the prime mover speed. By this manner the engine speed is merely a function of power enabling the vehicle, for example, to travel at rated speed, but at an optimum or low engine speed when the terrain is flat or when little power is needed.

In conventional mechanical or hydraulic drive systems, the speed of the engine is directly proportional to the speed of the vehicle in addition to being directly proportioned to the power required so that at high vehicle speeds alone the fuel economy drops off considerably. The overall weight of a standard transmission differential drive and the electrified propulsion version briefly described is approximately the same, but the latter has advantages which include a more economical fuel operation.

The electrified vehicle immediately suggests the possibility of using for other purposes the electrical energy available when the vehicle is at rest. This can be accomplished by controlling the generator frequency as before (mainly a net work of electronic components, a controlled frequency reference, and controlled silicon rectifiers whereby a sine wave is virtually "pieced together") but at a fixed point, probably 400 cycles and independent of engine rpm. Again, the prime mover speed is a function of power to suit the demand and in this role also operationally economical. In addition, the entire weight of a separate prime mover-electrical generator plant is eliminated. The electrified vehicle components are a portion of the vehicle.

In this study it is proposed only to assign a dual mode so that the power already available can be applied to the MHD-laser weapon when the vehicle is at rest. To take advantage of the on-board power and satisfy the input requirements of the magnetohydrodynamic generator, time-thermal characteristics must again be resorted to which again involve a pulsing or surging technique. Available vehicle engine horsepower with the vehicle at rest is taken as 75 per cent for the weapon with 25 per cent reserved for applications discussed later. In the case of the M113, this apportions about 160 hp to the 2.5-nm weapon and in the case of the M60 about 560 hp to the 25-nm weapon. Translating this to kilowatts at or near sea level operation amounts to approximately 100 kw and 370 kw, respectively, at continuous operation. The input power requirements to the MHD, mainly for the magnetic portion, is taken as 8 to 80 mw peak for a total time of 8 msec/sec for the 2.5 and 25-nm Laser weapon systems, respectively. The theoretical capabilities of the applicable input power plants during this time interval are approximately 12 and 46 mw. These capabilities will not be practically realized because of the electrical characteristics, particularly impedence of the electrical circuit and reluctance of the magnetic circuit. Moreover the 46-mw theoretical capability of the M60 does not meet the 80-mw requirement for the 25-nm weapon in that the 8-msec time frame must be reduced to two (the minimum), resulting in a pulse repetition rate of one per second in lieu of four as originally planned. At a PRF of one, the theoretical capability of the input power source is 92 mw or only about 13 per cent more than the demand.

It is evident from this analysis that continuous output at high-energy levels maintained over a long period of time is not now feasible and may not be practical for many years. The first continuous propagation breakthrough can probably be expected from the laser module itself,

particularly in the area of the laser medium. To realize any overall advantage as an integrated weapon, a similar breakthrough will be necessary for the power end of the system. Nevertheless, the pulsing approach is attractive and familiar as analogous to a radar concept, both for attaining peak levels of power and systematic scanning. Pulsing the output of the power source, which serves as the input to the magnetic field of the magnetohydrodynamic generator, at a predetermined rate so that its output is in turn pulsed, and finally pulsing the laser, may prove feasible.

Operational environment of a mobile Laser weapon system is an important design consideration and, in addition, relates directly to power generation. In general, if the Laser weapon and its power supply are designed at the same level of ruggedness, minimum operating ease, non-susceptibility to chemical, bacteriological, radiological, temperature, dust and humidity environments, safety, crew comfort, and atmospheric pressure conditions as the carrier (human or vehicle), such design would be considered adequate and satisfactory. No system gains can be realized by over designing the laser weapon portion in any of these categories over and above the carrier. The integrated system as a chain will only be as durable and effective as its weakest link. Environmental criteria, therefore, for the laser module and its companion power supply should conform to that used for the carrier. Behavior of the engine, when the carrier is a vehicle, under atmospheric pressures other than at sea level and at temperature extremes have long been areas of concern in missile and rockets systems, and it is believed that in some instances the importance of these was over emphasized. Army Regulations AR 705-15 dated 17 August 1957 set forth the environmental conditions governing Army equipment. Briefly three general categories, basic (-25 to ± 115°), extreme cold (-65°), and extreme hot (+125°), are outlined with elevations ranging from 3,000 to 8,000 feet. Military Standard MIL-STD-210A of 2 August 1957, approved by the Department of Defense, however cites altitude extremes of 1,300 feet below sea level to 18,000 feet above sea level.

15. <u>(S) Target Acquisition</u>. Target acquisition for the two longer range Laser weapons postulated will require more than visual, optical, or infrared illumination as suggested for the lesser ranges for day and night operation. Again, using the Laser itself for search and acquisition creates an additional power demand of a magnitude that does not offer an attraction. It is doubtful that the Laser will ever supplant radar for these general purposes, and for these reasons 25 per cent of the horsepower engine capabilities were reserved partly for on-board auxiliaries ("housekeeping", cooling, pumps, etc.) and the remainder

for radar use. Allowing 50 per cent of this for Laser associated auxiliaries and other miscellaneous needs leaves approximately 16 kw for the 2.5-nm Laser radar and 62 kw for the 25-nm Laser radar. For a target with a radar cross section of 0.01 m^2 the radar range is approximately 83 nm and 108 nm with 16 kw and 62 kw input power, respectively (see Figure 11).

Such ranges exceed considerably the range capabilities anticipated for the Laser weapon so that reasonable time is allowed after acquisition for final readiness preparations, communications with higher command or sister units, and target discrimination. Slaving the Laser weapon to the radar antenna and using simple computer techniques to fire at optimum range and effect optimum effectiveness can reduce human time lag to "push button" operation making the time between acquisition and firing more than ample. By similar streamlining and automation the entire operation will reduce itself basically to one of decision - to fire or not to fire. If a missile traveling at 25,000 fps was detected at 108 nm approximately 20 sec will elapse before it comes within the 25-nm range of the long range Laser weapon. During the boost phase, the velocity of the missile would be considerably less and the available time would be increased accordingly.

B. (C) Guidance

Semiactive guidance seems to be the most attractive method of guidance at the present time. Beam riding appears to have possibilities as a second choice. With the present state-of-the-art, command guidance is not too appealing; however, with further development in modulation methods, better steering methods and decreasing problems of atmospheric conditions, such as going to other regions of the electromagnetic spectrum, this type of guidance may become more appealing.

There is little doubt that laser optical range finders will be used in the near future. Several laser optical range finders with more than 3 mw peak power output have been developed at the Signal Research and Development Laboratory at Fort Monmouth, N. J. This peak power output was accomplished by using a reflecting prism and a laminated rotating mirror to contain the light, instead of using mirrors as used in ordinary lasers.

Optical ranging systems incorporating a laser are severely handicapped by atmospheric effects such as haze. For example, a Sylvania

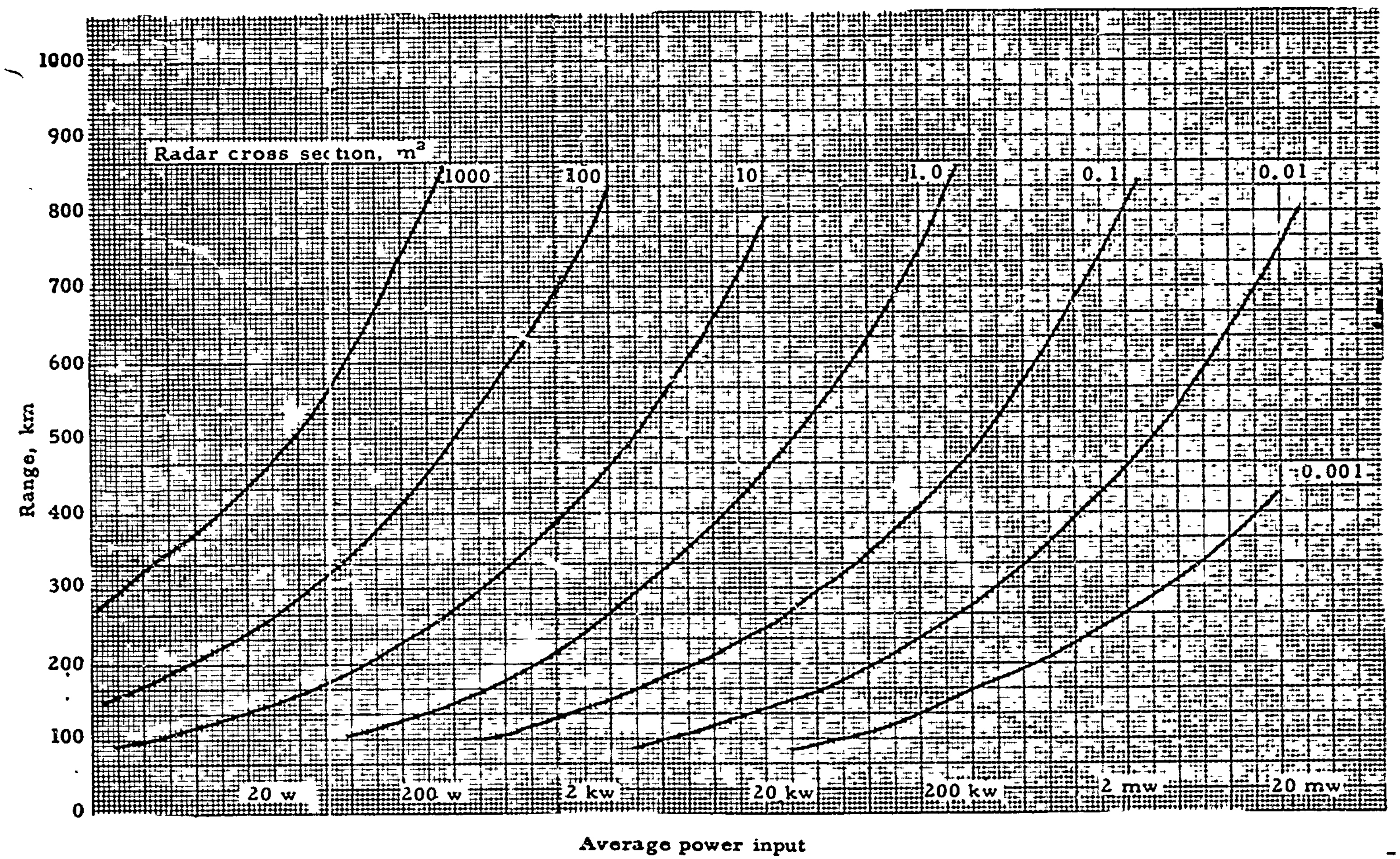


Figure 11. (S) TYPICAL COMPARISON CURVES OF RADAR INPUT POWER VERSUS RANGE FOR VARIOUS RADAR CROSS SECTIONS.

report shows that a laser delivering a megawatt in a one-microsecond pulse will have a range of approximately 3.5 miles in haze, whereas on an exceptionally clear day, operation is possible out to ranges in excess of 100 miles.

A laser used as an altimeter would have greater accuracy over a radar-type altimeter because it is able to concentrate the transmitted energy into a narrow beam. However, tracking of the fine thread of light by means of a stable platform and knowledge of missile behavior along its re-entry trajectory are problem areas. Compensation for the effects of spin, tumbling or other gyration, along with vibration of the missile and associated structures, will also be required to obtain system accuracy.

Techniques of obtaining narrow, predictable and periodic bursts from the laser, which are necessary in a ranging system, seem to be in the offing. One method is by the use of two pumping tubes. A ruby laser is pumped up to threshold by one lamp and short bursts of excitation are applied by the second flash tube with a periodicity that is short compared to the relaxation time of the excited chromium atoms. This results in a pulse of laser output in a controllable and periodic fashion.

The availability of predictable, controllable repetitive pulses not only eliminates some limitations of the laser, but makes possible the use of integration to increase the signal-to-noise ratio, range gates, digital readouts, and other sophisticated techniques.

For semiactive homing, the laser is used to illuminate the target. An optical receiver located in a missile would track the reflected optical signal and provide terminal guidance to missile impact. The development of compatible transmitter, receiver, and tracker necessary for this application seems to be feasible in the near future. Westinghouse is doing work along these lines using a phosphor pump and neodymium-doped rod. They are optimistic about developing an antitank missile system. They expect to be able to solve the target detection and tracking problems of radiated power generation and modulation, beam forming and detection of received signal power. The true signal is to be detected over other noise power by its magnitude, periodicity, and its spectral distribution. Noise associated with the intense solar background is to be reduced to a reasonably low value by using a long sampling time, moderate optical filtering, and a narrow field of view.

General Electric has proposed an air-to-ground semiactive guidance system using a pulse laser of high repetition rate to illuminate the target. At present General Electric has a laser operating at around 10 pps. A missile-borne receiver will be locked on the reflected beam before launch and will guide the missile to impact.

At present it seems that a fair weather semiactive guidance system is now possible. As far as is known, the atmospheric effects on a system have not been fully examined. It appears that these effects will limit the operation to a great extent. Natural atmospheric effects as well as man-made effects, such as smoke screens, may make the power requirement so high and cooling requirements so stringent that, with present state-of-the-art, a mobile system would not be practical. Development of adequate receivers for semiactive guidance may present problems, but they appear to solvable ones.

The feasibility of laser semiactive guidance for antitank missile systems seems very good, but will necessitate further development, such as efficient operation of the laser. Better pumping techniques and improved laser materials should provide better efficiency. Improvement of cooling methods should also increase efficiency. Ruby with a sapphire jacket has been used to gain higher efficiency. The sapphire jacket increases the area for better cooling and helps to focus the pump light more directly into the ruby.

General Electric is reportedly developing a pump source which gives off light almost entirely in the green region, thus providing more light energy to the ruby. This should increase efficiency of the ruby laser. Also a laser material, sodium terbium borate, which emits coherent light in the green region at very low energy input, has been developed by Semi-Elements, Inc. It appears that by cascading a laser of this type to a ruby laser, better efficiency can be obtained. Many other methods are being developed to help increase the present low efficiency of the laser.

Many other laser materials are also being investigated at the present time. They include solids, gases and liquids. Most gas lasers are low power, but provide continuous wave operation. According to reports, a gas which shows possibilities of high power operation is being investigated. A solid, calcium tungstate, has been reported as having a negligible threshold, which could help to increase laser efficiency. Little information on the progress of work on liquid lasers has been disseminated.

III. (C) CONCLUSIONS

Because of the practicability of converging, directing and concentrating Laser energy in a narrow beam, this weapon concept offers the most promise as a kill mechanism of the death-ray type and research and design along laser avenues should be pursued.

Research and development in the areas of electrical power generation and integrated mobility for field army laser weapons must be pursued. The general trend for field army weapons has shown that electrical power needs, mobility, and logistics are becoming more critical with each new application and weapon advancement. To utilize the anticipated effectiveness of the laser as a kill mechanism, the system must be mobile and satisfied with large blocks of average power and huge blocks of peak power.

The state-of-the-art of the MHD requires the same aggressive attitude of research and development as the Laser does to assure an integrated system. The need for integrating all modules of the composite system and tailoring these to suit such a system from the early beginnings cannot be overemphasized. Adapting major modules of general purpose equipment to suit the requirements of a specialized weapon can generally not be expected to produce optimum system performance. Any major module of an integrated Laser system is equally as important as its counterpart and weakness in any one will be evident in the married system.

It is further concluded that lasers should be looked at as an integral part of guidance systems. It appears that with the rapid advancements in the laser field, a guidance scheme could be developed in the near future, which would beneficially replace some of the existing antitank missile guidance systems. It is therefore suggested that emphasis be directed toward application of lasers to these types of systems.

Other critical areas to which laser research and development should be devoted are pumps, materials, optics, effects and atmospherics. An integrated effort to channel the results of such separate efforts into a coordinated requirement-oriented system concept will provide an early assessment of the capability of the laser as an entire weapon system, or as a part of a weapon system.

APPENDIX

ATMOSPHERIC ATTENUATION IN THE INFRARED REGION (U)

I. (C) INTRODUCTION

Atmospheric attenuation is an extremely important phase of the close-support Laser weapon system research. The purpose of this report is twofold; (1) to investigate the attenuation in the infrared region (0.72 to 14 μ), and (2) to plot some useful curves of transmission versus wavelength.

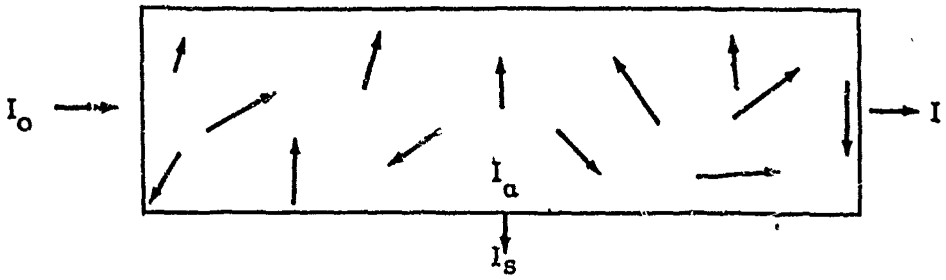
Attenuation can be attributed to several sources: molecular absorption, scatter due to haze and water vapor, and molecular scatter.

II. (U) ABSORPTION

Absorption exists in two forms, i.e., resonant and nonresonant cases. Nonresonant absorption can be expressed in terms of classical theory. A molecule is assumed to have its rotation resisted by a viscous force. The resonant absorption, however, cannot be considered classically, since absorption is discrete. Hence, quantum mechanics must be introduced to give the complex dielectric constant necessary for the explanation of the absorption. A substance shows general absorption if it reduces the intensity of the incident electromagnetic energy evenly over a wide band. Selective absorption exists when the absorbing medium selects and absorbs energy at one frequency (or any number of discrete frequencies) in preference to others.

III. (U) GENERAL SCATTERING EFFECTS

Scattering is often confused with absorption. Although the two effect attenuation, the methods are different in each case. To make the case for scatter more clearly defined, consider the following case.



Let the light intensity, I_o, be incident and I the transmitted light after attenuation. The diagrammed tube is filled with smoke and has a length d. Due to the attenuation, the intensity of the light leaving is less than the incident intensity.

$$I_o > I$$

For a given constant density of smoke, it has been found that the attenuation varies exponentially.

$$I = I_o e^{-\alpha r}$$

where α is the coefficient of absorption. The term "absorption coefficient" in this case is a misnomer, since the scattering and absorption coefficients are combined. In fact, most of the light is not absorbed but is scattered to one side by the smoke particles. I_s, the scattered intensity, is greater than I_α, the absorbed intensity. Both are related by

$$I_o = I + I_s + I_\alpha.$$

True absorption, which represents an actual disappearance of the light, effects a temperature rise due to the additional excitation given the molecules of smoke. In the chamber under consideration, however, very little temperature rise is evident. The absorption coefficient therefore must be very small and would not be appropriate in this case.

Molecular scattering follows the familiar λ^{-4} law proposed by Rayleigh. However, small variations can occur in the scatter coefficient due to seasonal changes in the whole extent of the atmosphere as well as in the water vapor content and possibly in the number of very small water droplets of a diameter less than 0.02 μ.

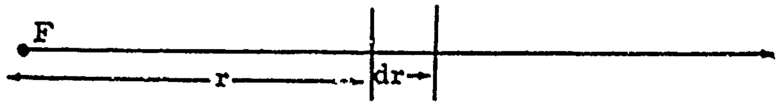
IV. (U) TOTAL TRANSMISSION

In general, α is considered to be the sum of α_s and α_a. The attenuation equation then becomes

$$I = I_o\, e^{-(\alpha_a + \alpha_s)r}$$

which is known as Lambert's Law.

Lambert's Law may be found more quantitatively by considering a collimated, monochromatic beam of light having a flux, F, at a cross section of distance, r, from the origin of the beam.



By reasoning, it may be seen that a unit thickness of the medium will scatter (or absorb) a beam proportional to the incident flux, F. Then

$$dF = -\, bF dr$$

$$dF/F = -\, bdr$$

integrating, and using F_o as the constant of integration

$$\ln F = -\, br + \ln F_o$$

exponentiating

$$F = F_o e - br,$$

where b can be either the coefficient of scatter, α_s, or the coefficient of absorption, α_a.

If, as usual, both scatter and absorption are present and are operating together, the coefficient of extinction is introduced and is simply the sum of α_a and α_s.

Extinction $(\alpha) = \alpha_s + \alpha_a$. Letting $b = \alpha$, the flux equation becomes $F = F_o e^{-\alpha r}$. This is the form that Lambert's equation takes. The transmissivity may be written as

$$t = t_o e^{-\alpha}.$$

Then the transmittance, T, is

$$T = t^r.$$

Combining the last two equations gives

$$T = (e^{-\alpha})^{r}$$

$$= e^{-\alpha r}.$$

Solving the flux equation for $e^{-\alpha r}$,

$$F/F_o = e^{-\alpha r}.$$

Then the transmittance $T = F/F_o$, of I/I_o. These are interchangeable because flux and intensity have the same basic dimensions.

V. (U) HAZE SCATTERING EFFECTS

The scattering due to haze is more difficult to consider than simple Rayleigh scatter for molecular-sized particles. Haze particles average from 0.3 μ for a light haze to 0.4 μ in diameter for a heavier haze. Since the λ^{-4} Rayleigh scatter law holds only for particles much smaller in diameter than the wavelength, another method must be used to calculate the effect of haze upon attenuation.

Referring to the general formula,

$$I = I_o e^{-\alpha r}.$$

The value of α for haze scatter may be expressed in A. Angstrom's empirical equation

$$\alpha \sim \lambda^{-\gamma}$$

where $\gamma = 4$ for Rayleigh scatter, and $\gamma = 0$ for neutral scatter.

The values of γ will vary between 1 and 2 for a normal atmosphere (Schüepp, 1949). If $\gamma < 1$, there are relatively large particles involved and there will be a white ring around the sun. This is a good method of estimating the particle size of the haze. If $\gamma > 2$ the sky is fairly bright blue in spite of strong turbidity.

In the equation

$$I = I_o e^{-\alpha r}$$

for single scattering, α is dependent upon the size of the particle, and the index of refraction. Because these quantities are never all known in

practice, the transmission at some predetermined wavelength is used as a standard. In Figure 12, 0.61 μ is the standard value.

In considering a haze problem, the visibility in nautical miles is often quite useful as criteria for measuring the density of the haze. An experimental relationship for a haze of known visibility has been found to be

$$V(\text{nautical mile}) = 3.92/\alpha.$$

This relationship is good, as far as it goes, but often the value of α varies greatly from day to day without any appreciable effect on the visibility. This is due to the variation in diameter and distribution of haze particles. Hence, a haze cannot be described completely by a visibility measurement alone, or by the use of transmission coefficient at a given frequency.

VI. (U) WATER VAPOR EFFECTS

Water vapor also presents a difficult problem. A relative humidity test is not sufficient for expressing the attenuation of a given amount of vapor. Since α changes rapidly with wavelength, a large number of calculations would be required to give the attenuation due to the vapor over a broad band of wavelengths.

The large mass of calculations which would be necessary if individual α's are considered for each wavelength may be reduced greatly by employing a relationship that describes the integrated absorption over a wide spectral range.

The spectrum exists in eight windows as shown in Table III. As may be noted from the solar absorption spectrum (Figure 13), these eight windows extend from center-to-center of successive absorption bands. As the amount of water vapor (w) n a given pathlength (in this case 2,000 yd) increased, the additional absorption caused by the addition of a small amount of water decreased, and the empirical equation

$$dI = - I_o k_i \frac{dw}{w}$$

is applicable.

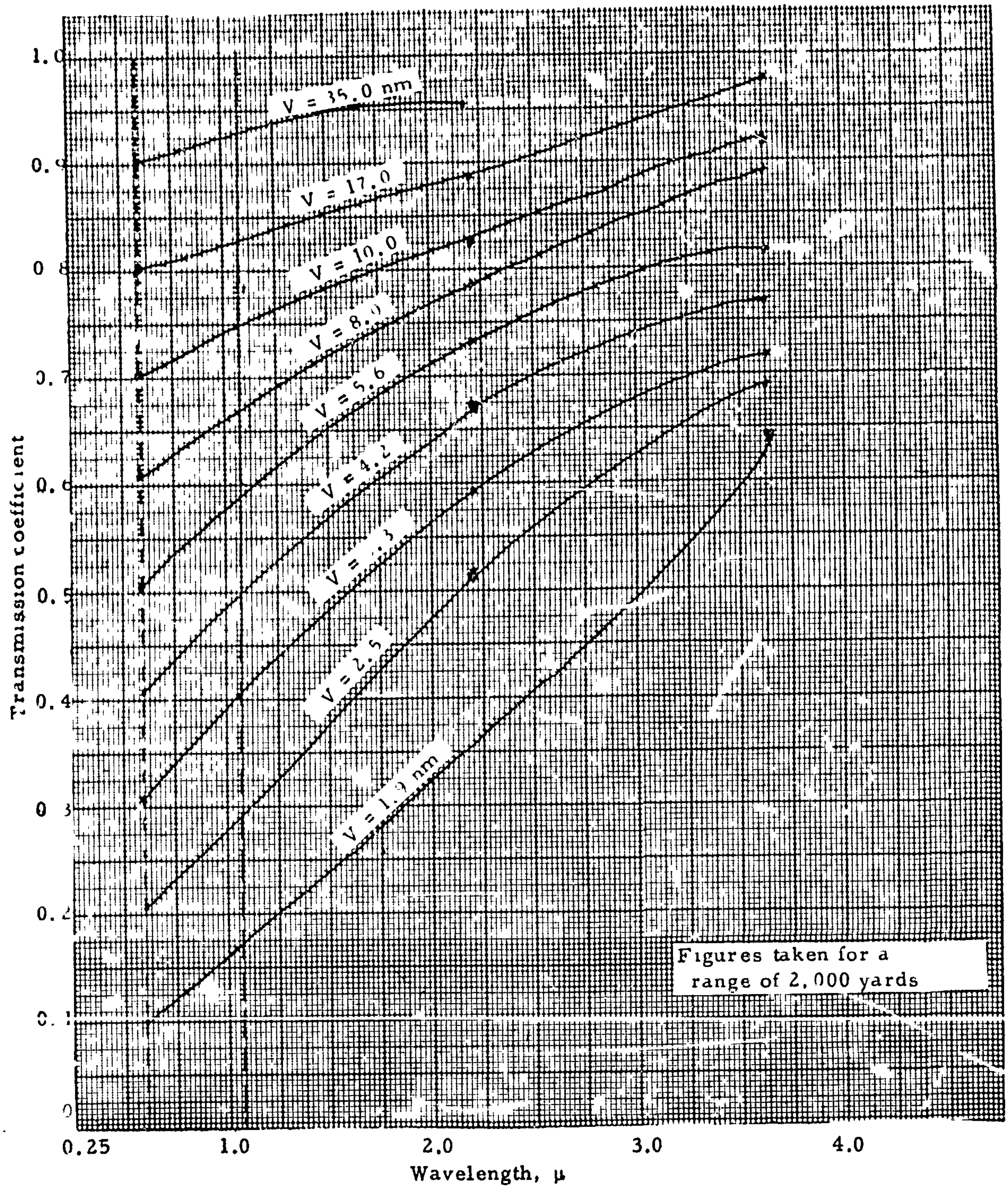


Figure 12. (U) THE RELATIONSHIP OF TRANSMISSION THROUGH DIFFERENT DENSITY HAZES VERSUS WAVELENGTH IN MICRONS.

Integrating and using t_o as a constant of integration,

$$I = -I_o k_i \ln w + t_o.$$

Table III

(U) WINDOW REGIONS IN THE INFRARED

	Window wavelength, μ	k_i	t_o
I	0.72 - 0.92	15.1	106.3
II	0.92 - 1.1	16.5	106.3
III	1.1 - 1.4	17.1	96.3
IV	1.4 - 1.9	13.1	81.0
V	1.9 - 2.7	13.1	72.5
VI	2.7 - 4.3	12.5	72.3
VII	4.3 - 5.9	21.2	51.2
VIII	5.9 - 14.0	---	---

Rearranging

$$\frac{I}{I_o} = -k_i \ln w + t_o$$

where

$\frac{I}{I_o} = t$, the transmission coefficient. By using the constants k_i and t_o, which are peculiar to a particular window region, the transmission, t, may be found. See Table III for these values. The constants are calculated from experimental data obtained from many sources for varying amounts of water vapor to 200 mm.

VII. (U) HAZE EFFECTS

It must be recalled, however, that the above equation does not allow for the attenuation of the haze in the atmosphere. The transmission of the haze can be estimated separately and then applied as a multiplying factor. For example, Figure 14 shows a transmission of 0.6 for 10 mm of water vapor for the window region of 1.9 to 2.7 μ

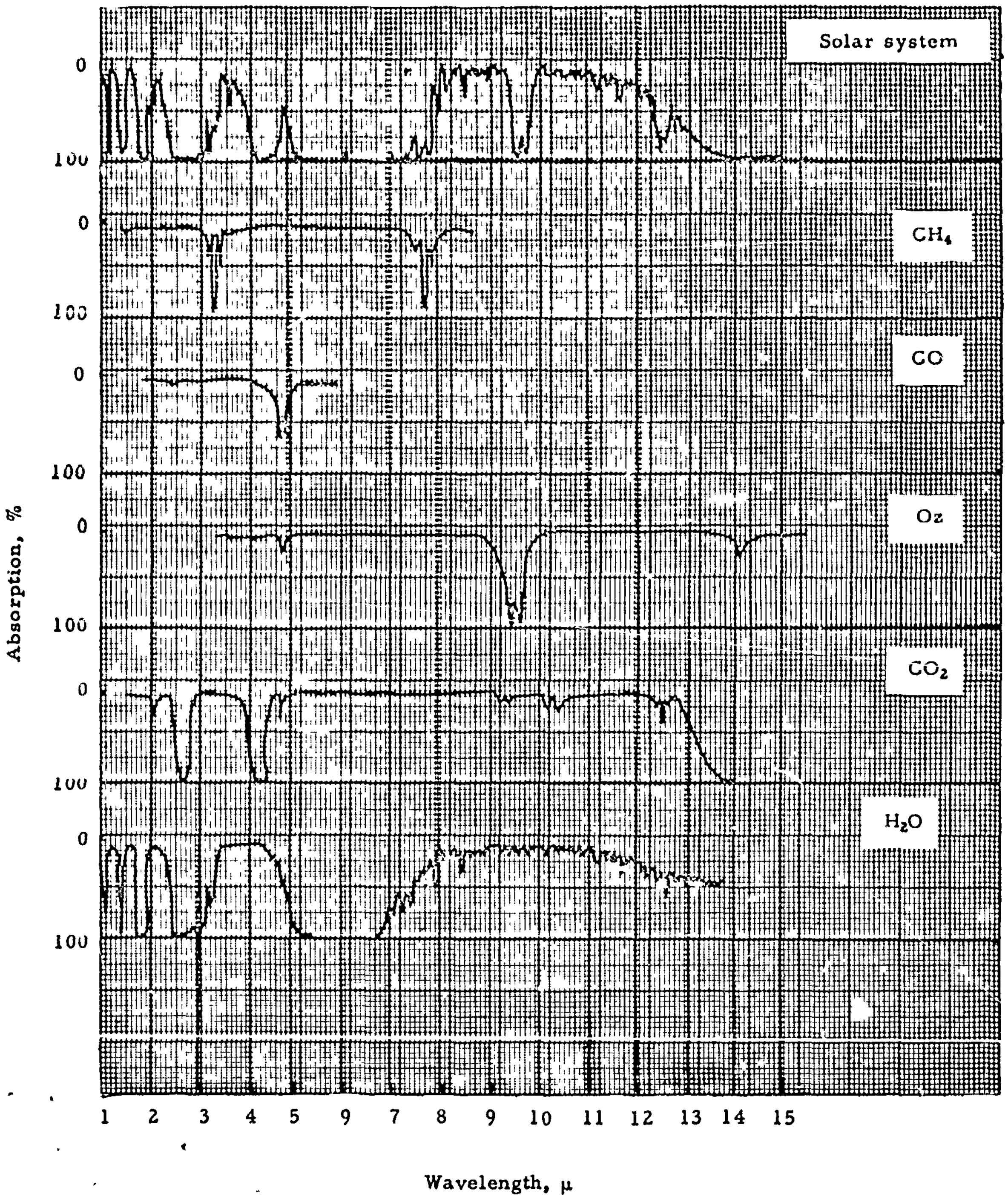


Figure 13. (U) ABSORPTION SPECTRA FOR DIFFERENT GASES IN THE NEAR INFRARED REGION.

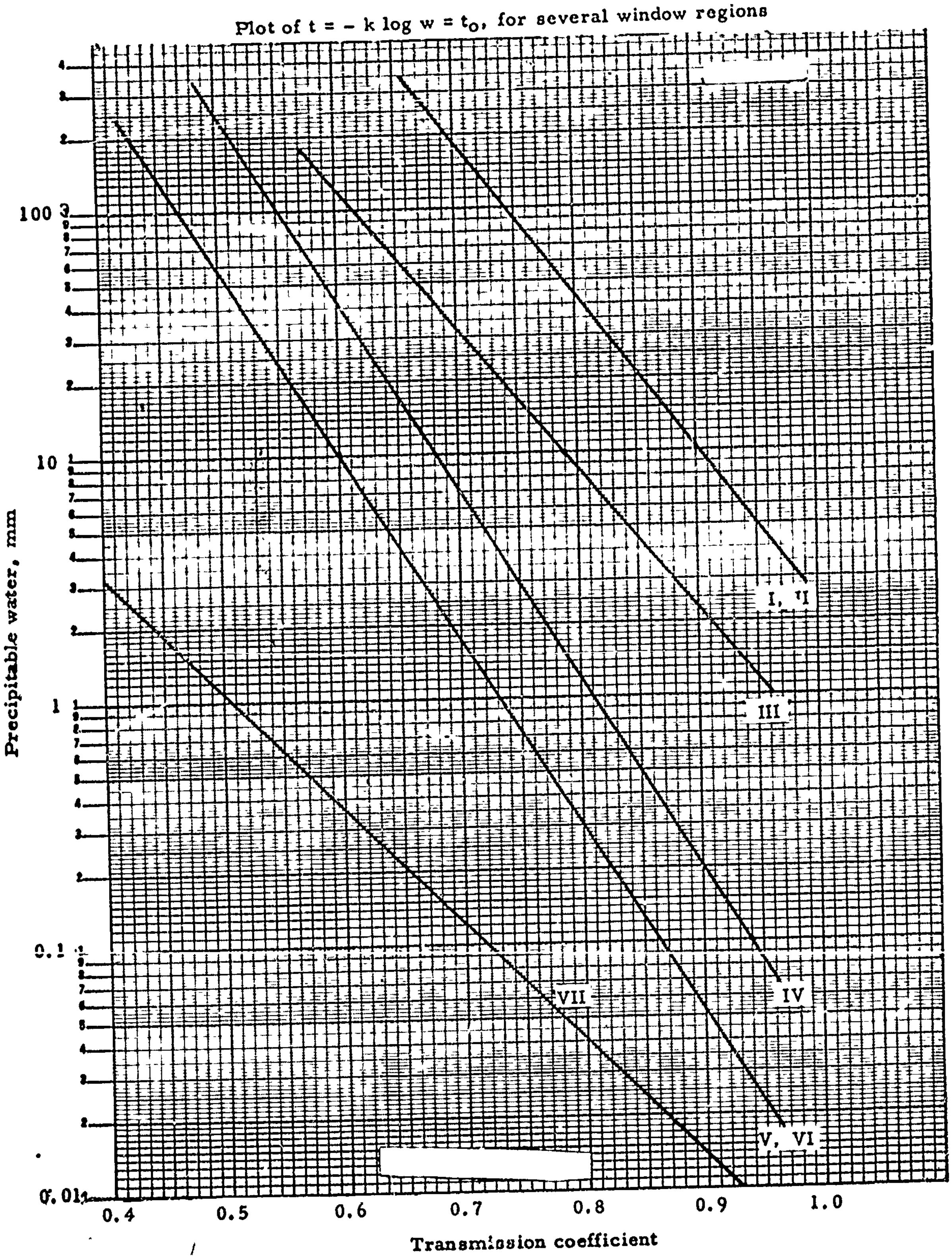


Figure 14. (U) TRANSMISSION VERSUS PRECIPITABLE WATER.

(Curve V). For a medium haze of visibility 2.5 nm, Figure 12 can be used to find the approximate haze attenuation. T_h varies from 0.47 at 1.9 μ to 0.59 at 2.7 μ. The average value at 2,000 yd is 0.53. From the graph at 2.3 μ, the average or "center" of the window, the transmission is read at 0.54. Therefore, it is safe to assume that the haze transmission at the center of the window is valid and can be applied to the overall transmission as a multiplied factor.

$t_{tot} = t_w \times t_h = 0.54 \times 0.6 \approx 0.32$, the transmission of the atmosphere under these conditions.

Because the haze transmission varies exponentially, i.e.,

$$t_h = e^{-\alpha r}$$

and t_w in the window is only a first order approximation, the role of the haze attenuation will be much greater than that of the water vapor attenuation at longer ranges than the constant 2,000 considered here.

VIII. (S) EXAMPLE TRANSMISSION CALCULATION

How much power must a 1.06 μ Laser close support weapon liberate to melt a hole in a 2-inch steel plate at 2,000 yards under the atmospheric conditions of 0.1 mm of water vapor, and a visibility of 17 nm?

The incident energy required to melt a hole in 2 inches of steel at 2,000 yards is 3×10^4 joules.

To figure the attenuation, first find t_w, then find t_h and multiply for the total attenuation.

t_w: 1.06 μ is in the second window having the range of 0.92 μ to 1.1 μ. Figure 14 shows that the 1.06 μ absorption from water vapor has no particular effect on the total attenuation. Hence, the haze will be the only effective attenuator.

t_h: Figure 12 gives a value for t_h of 0.8125 for a visibility of 17.0 nm and 1.06 μ.

The total power required under these conditions would then be

$$(0.8125)(\text{power output}) = \text{incident power} = 3 \times 10^4 \text{ joules}$$

$$\text{power output} = \frac{3 \times 10^4}{0.8125} = 3.75 \times 10^4 \text{ joules required.}$$

This is a typical calculation. Had the wavelength been longer or the water vapor density higher, the water transmission factor would have been considered. Certain obvious criteria would have to be considered in selecting a final useful frequency. Points where the transmission is high are good wavelengths to choose to observe the solar absorption spectrum since the atmosphere is least absorbent at these peaks. It has also been observed that at shorter wavelengths water vapor effects become negligible.

The growing interest in neodymium-doped glass rods as lasing substances is due in part to the fact that the output wavelength of 1.06 μ lies within an atmospheric window, a point at which the transmission is high. Because of this interest and the potentialities of making a cheap lasing rod in this region of the infrared, further consideration of this region's attenuation is warranted.

IX. (U) PRACTICAL TRANSMISSION CONSIDERATIONS

There are several sources of atmospheric attenuation to be considered; molecular scatter and absorption, which concern particles much smaller than the wavelength; Mie scatter and absorption, which are treated together under haze attenuation; and water vapor losses.

Figure 15 shows the average amount of precipitable water in the atmosphere by months for the year 1961 in the Redstone Arsenal area. An average value was then calculated for the year.

The graph shows an average for the whole month, days and nights. The cooler early-morning temperatures will cause the precipitable water level to rise higher than the norm for the day, whereas the early afternoon, because of the higher temperature, will experience a marked drop in the precipitable water.

Assuming, however, that a laser weapon system must be functional night and day, the average calculated is acceptable for the following attenuation calculations.

The transmission through water vapor, t_W, can be calculated directly from Figures 14 and 15. The average precipitable water in

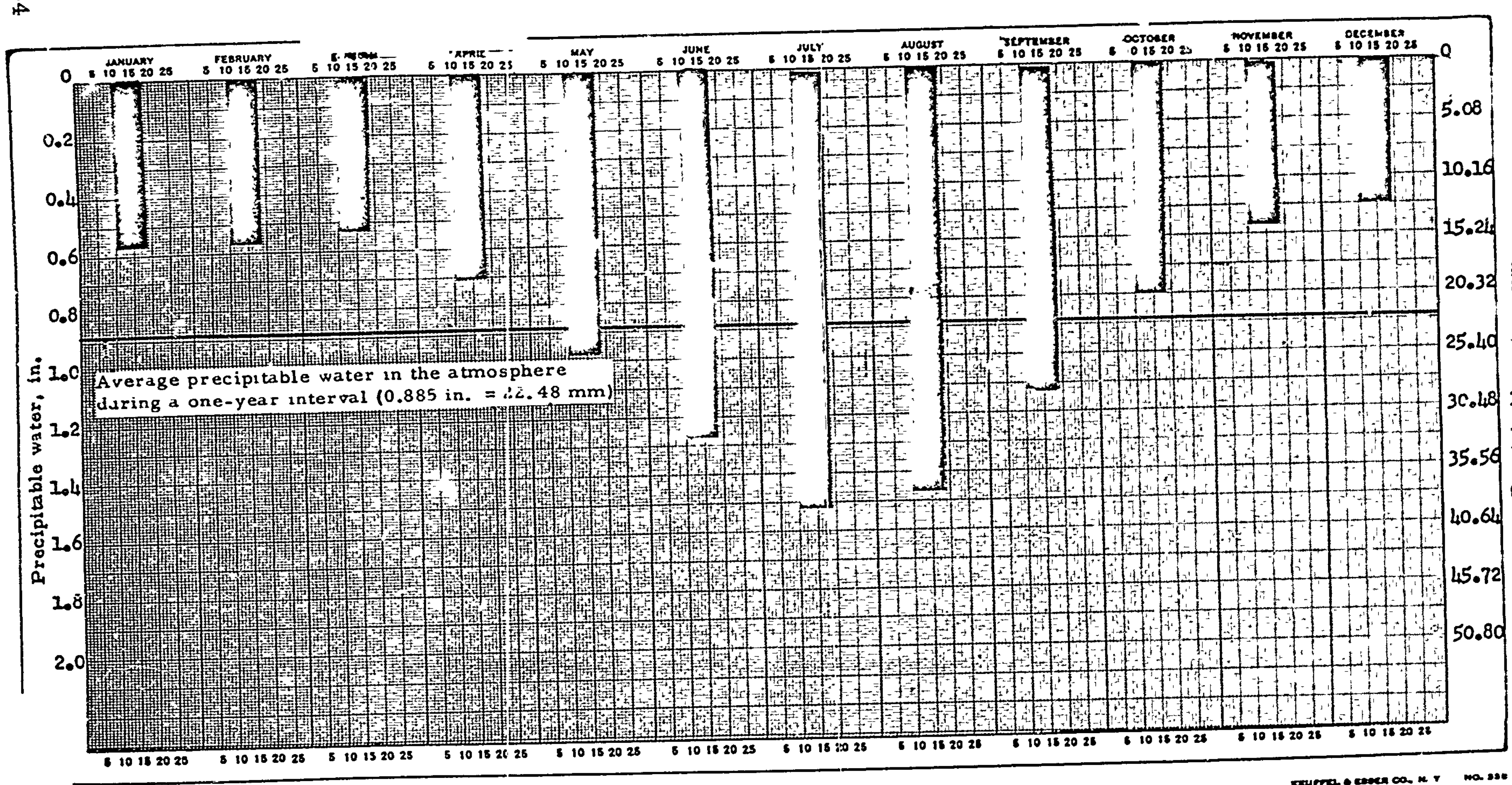


Figure 15. (U) AVERAGE PRECIPITABLE WATER IN THE REDSTONE ARSENAL ATMOSPHERE.

the atmosphere is 0.885 in. or 2.248 cm. Figure 14 shows that in the region of Group II (0.92 to 1.1 μ) the effective transmission = 0.847.

For the average water level, $t_w = 0.847$.

For the maximum water level, which occurs in July, (38.6 mm), the transmission $t_w = 0.806$.

The visibility for the Arsenal area varies widely from day to day, but a winter average of 5 nm, and a summer average of 22 to 25 nm are good estimates. These estimates are substantiated by the Huntsville Weather Bureau, which give a yearly estimate of 10 to 12 nm. The visibility will vary from morning to night much as the precipitable water does. If ground fog occurs, it generally lifts by 0800, and rarely sets in before midnight.

The transmission through haze can be readily found in Figure 12 which is derived from the relationship

$$V = \frac{3.92}{\alpha}.$$

For a visibility of 12 nm, $t_h = 0.77$; for the lowest visibility (5 nm), $t_h = 0.54$.

The effect of absorption in the optical region was calculated by B. Zanotelli (1940), on the assumption that the coefficient of absorption k is small enough to permit the approximation

$$1 - e^{-2ka} \approx 2ka.$$

Since k is approximately 2×10^{-2}/cm for water, this assumption is valid for it and other materials, since k is near a maximum for water.

The flux absorbed by one particle at an illuminance of 1 lumen/cm²

$$F_a = \frac{4\pi ka^3}{3\mu_r} \text{ lumens/lumen/cm}^2$$

where μ_r = index of refraction.

Substituting 4/3 as the index of refraction for water,

$$F_a \approx \pi ka^3 \text{ lumen/lumen/cm}^3.$$

From the Mie theory, the total scattering coefficient k is given:

$$F_s = NK\,\pi a^2 \text{ lumens/lumen/cm}^2.$$

Since only one particle is being considered, and no interactions are being allowed for,

$$F_s = K\pi a^2 \text{ lumens/lumen/cm}^2.$$

For a drop of water, the scattering area ratio K is nearly 2, so

$$F_s = 2\pi a^2 \text{ lumens/lumen/cm}^2.$$

Assume a droplet of radius 10 μ (10^{-3}cm).

The amount of scattered flux

$$F_s = 2\pi a^2 = 6.3 \times 10^{-6} \text{ lumens/lumen/cm}^2$$

whereas, the amount absorbed $F_a = ka^3 = 6.3 \times 10^{-11}$.
Then

$$\frac{F_a}{F_s} = \frac{\pi k a^3}{2\pi a^2} = \frac{6.3 \times 10^{-11}}{6.3 \times 10^{-6}} = 10^{-5},$$

which amply justifies any neglect of absorption effects in the optical range. Even if the particle size had been increased to 1 cm in diameter, the F_a/F_s ratio still would be only 0.05.

This effect has been shown for water vapor. For carbon and tar in city smoke, the Mie theory can be used by introducing a complex index of refraction. This "haze" effect has been treated more qualitatively in a previous section of this report. The molecular absorption is 1.06 μ. This can be easily seen by examining the absorption spectra for those materials in Table IV. The most abundant materials have no dark line in the 1.06 μ region; hence, the effects of molecular absorption can be neglected.

Molecular scatter, commonly called Rayleigh scatter takes the form of

$$k_s = 24\pi^3 N\left(\frac{m^2 - 1}{m^2 + 2}\right)^2 \frac{V^2}{\lambda}4$$

where k_s is the amount of incident energy scattered, N is the number of molecules per cubic centimeters, m is the index of refraction and V is the scattering particle volume.

Table IV

(U) ABUNDANCE OF ATMOSPHERIC CONSTITUENTS
(AT - CM)

Constituent	Abundance	Percentage
N_2	624,600	77.588
O_2	167,600	20.819
A	7,440	0.924
CO_2	320	0.0398
Ne	14.6	0.00183
He	4.2	Neg.
CH_4	1.2	Neg.
Kr	0.8	Neg.
N_2O	0.4	Neg.
H_2	0.4	Neg.
Xe	0.06	Neg.
Oz	0.2 - 0.3	Neg.
CO	0.6 - 0.15	Neg.
H_2O	10^3 - 10^2	0.621
		99.994

For a gas, the factor (m − 1)V refers to a specific molecule. This product is a constant for a given gas and can be written thus

$$(m - 1)gas = N(m - 1)V = \rho c.$$

The gas density, ρ, varies with the number of particles per unit volume.

After substituting

$$(m - 1)gas = N(m - 1)V,$$

Rayleigh's Law becomes

$$k_s = \frac{32\pi^3}{3N\lambda^4} (m - 1)^2 \text{ gas}.$$

At sea level, $(m - 1)^2$ gas = $293^2 \times 10^{-12}$, a constant almost entirely independent of wavelength. The number of molecules, N, per cubic centimeters at sea level can be obtained from Avogadro's rule which states that one mole of gas at standard conditions occupies 22.4 liters of volume and consists of 6.023×10^{23} molecules.

$$22.4 \text{ liters} = 2.24 \times 10^4 \text{ cm}^3$$

$$6.023 \times 10^{23} \text{ moles}/2.24 \times 10^4 \text{ cm}^3 = 2.68 \times 10^{19} \text{ molecules/cm}^3.$$

At a useful range for a laser weapon system, e.g., 2,000 meters, the expression becomes

$$k_{sz} = \frac{32\pi^3 \times (2.93)^2 \times 10^{-12} \times 2 \times 10^4 \text{ cm}}{3 \times 2.68 \times 10^{19}/\text{ cm}^3 \times \lambda^4 \text{ cm}}$$

$$k_{sz} = \frac{(30.95)(32)(293)^2(2) \times 10^4}{8.04 \times 10^{19}\lambda^4}$$

$$= \frac{2.21 \times 10^{-19} \text{ cm}^4}{\lambda^4 \text{ (in cm)}}$$

$$1.06\ \mu = 1.06 \times 10^{-4} \text{ cm}$$

$$(1.06 \times 10^{-4} \text{ cm})^4 = 1.262 \times 10^{-16} \text{ cm}^4$$

$$k_{sz} = \frac{2.21 \times 10^{-19} \text{ cm}^4}{1.26 \times 10^{-16} \text{ cm}^4}$$

$$k_{sz} = 1.75 \times 10^{-3}$$

$$= 1.75 \times 10^{-1}\% = 0.175\% \text{ scattered.}$$

It becomes evident that the atmospheric attenuation due to Rayleigh scatter is so low that it may be considered negligible.

Under the most adverse conditions in this area, the total atmospheric transmission at 1.06 μ would be

$$t_{atmosphere} = t_w \times t_h \times t_{absorption} \times t_{scatter}$$

$$= 0.806 \times 0.54 \times 1 \times 1 = 0.435.$$

Hence, under relatively heavy weather conditions, the atmospheric transmission is 0.435.

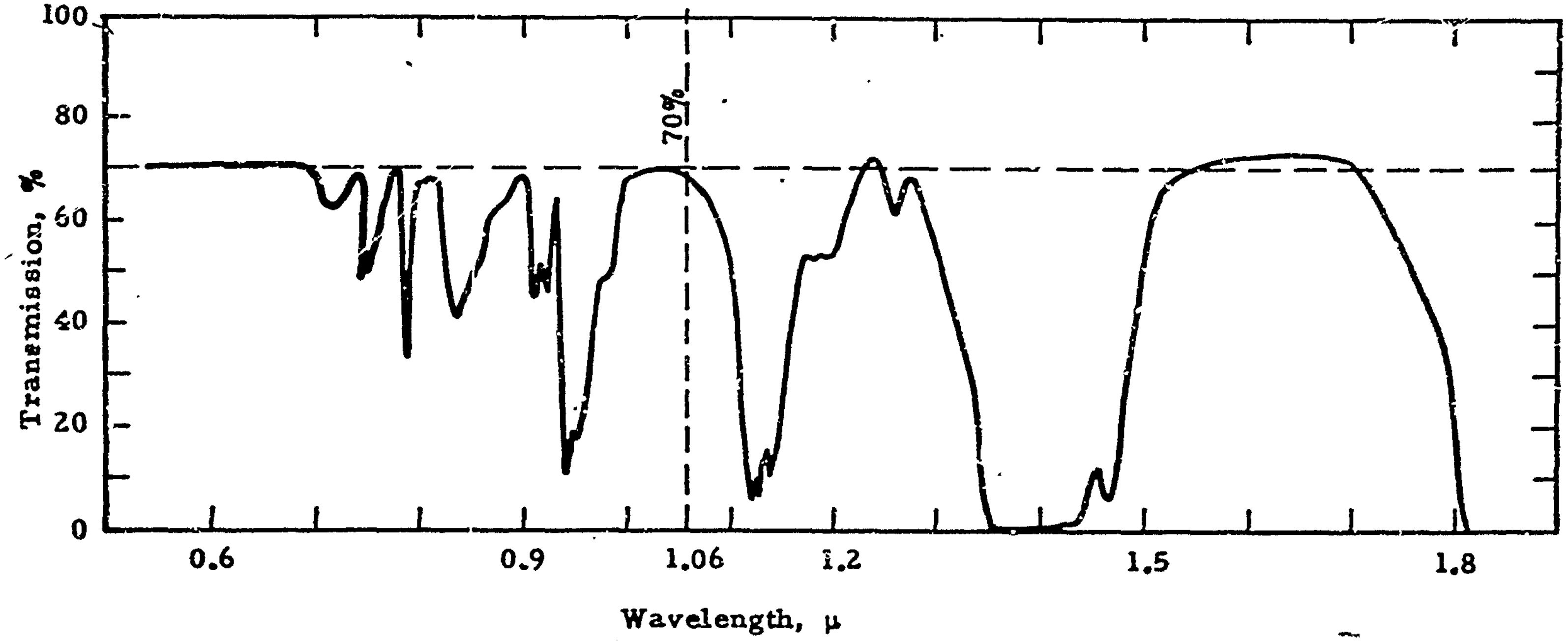
Under average conditions, the transmission rises, however, and

$$t_{atmosphere} = t_w \times t_h \times t_{absorption} \times t_{scatter}$$
$$= 0.847 \times 0.77 \times 1 \times 1$$
$$= 0.65.$$

Ordinary atmospheric conditions will then allow 65 per cent of the incident light to travel the 2,000 meters to the target.

These calculations are substantiated somewhat by Figure 16, which shows about 69 per cent transmission for a pathlength of 5,500 meters. However, the visibility used in Figure 16 was 32.4 nm, opposed to 12 nm used in the preceding calculations. The figure shows 41.8 mm of precipitable water, whereas the calculations used 22.8 mm.

The values in this report are sufficiently accurate to be useful in actual systems concept calculations where fairly precise values are needed. This report does not treat any effects the high-energy laser beam may have on the water vapor, molecular structure, etc., of the atmosphere.



3.4-mile (5.5-km) path
Temperature 64°F, r.h. 82%
18 cm precipitable water vapor
Daylight visual range 37.3 miles (60 km)
Measured transmission at 0.55 μ = 70%

Figure 16. (U) TOTAL TRANSMISSION FROM 0.6 TO 1.8 MICRONS.

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David A. Mendel

DAVID A. MENDEL

Chief, Systems Integration Branch

H. A. Dihn Jr

for WILLIAM C. McCORKLE, JR.

Director, Advanced Systems Laboratory

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